A STUDY OF MECHANICS OF TRIAXIAL FABRIC

A THESIS

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A STUDY OF MECHANICS OF TRIAXIAL FABRIC

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I also which to express appreciation to Professors Boteler and Tayebi for their service on the reading committee.

I am grateful to Doweave, Inc. for supplying the triaxial fabric which made this research possible.

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SUMMARY

The research was conducted to evaluate and to understand the mechanical response of triaxial fabric. Triaxially woven fabrics, formed by the intersections of three sets of yarn elements, have mechanical properties that are significantly different from those of conventional biaxial fabric produced from two intersecting perpendicular sets of yarns. In particular, the variation of mechanical properties with fabric orientation is expected to be smaller for triaxial fabrics than for biaxial fabrics; that is, the triaxially woven fabrics are more closely isotropic.

The triaxial fabric and a range of comparable biaxial fabrics were evaluated and compared for various structural and mechanical properties. The air permeability of triaxial fabric proved to be much greater than that of comparable biaxial fabrics with approximately the same percentage open area. The shear resistance of the triaxial fabric proved to be greater than that of comparable biaxial fabrics and could have been made even greater if the out-of-plane buckling of one of the sets of threads could be prevented. The tensile properties of triaxial fabric remained more isotropic than those of comparable biaxial fabrics only when wide specimens were tested. The triaxial fabric exhibited much greater isotropy in its bending behavior than comparable biaxial fabrics. The tearing response of the triaxial fabric was found to be quite different from that of comparable biaxial fabrics and yielded surprisingly high tearing strength when compared to biaxial fabrics. The

ball burst strength of triaxial fabric proved to lower than that of comparable biaxial fabrics.

CHAPTER I

INTRODUCTION

Purpose of Research

This research was conducted to evaluate and to understand the mechanical response of triaxial fabric.

History of Triaxial Fabric

Weaving of fabrics, one of the oldest of the arts, has always involved from two sets of intersecting perpendicular yarns. However, triaxial structures have been produced histroically in basketry and snowshoe constructions. It was not until recently that a systematic exploration of vast range of possible triaxial weaves was carried out by Doweave Inc.

Statement of the Problem

The presence of three sets of yarns sixty degrees apart in triaxial fabric will make the mechanical properties significantly different from the biaxial fabrics. It should be more nearly isotropic, i.e., it has approximately the same mechanical properties in all directions. It appears that the triaxial structure might offer advantageous properties in certain applications, thus a comprehensive experimental evaluation is necessary to clearly demonstrate the relative merits of triaxial fabric.

Method of Attack

perties were compared to comparable biaxial fabrics; then, the mechanistic understanding of the response of triaxial fabric was developed.

Review of Literature

The exploration and possible exploitation of the vast range of possible triaxial weaves and its process have only been carried out recently. The Doweave Inc. got the first patent for its process in weaving triaxial fabric (1,2).

The first studies in triaxial fabric were the feasibility of weaving triaxial fabrics in tight, low porosity configuration and the investigation of the stability and isotropy of triaxially woven fabrics. A detailed analysis of yarn motion required in triaxial weaving cycles has been done and disclosed. There was no fundamental problem involved in preventing the achievement of tight woven fabrics with fine yarns. A breadboard loom was developed here and used to weave the sample fabrics (3).

In Fabric Research Laboratories a more efficient loom was designed. In this loom the shedding and warp yarns indexing motion are controlled by a series of cams on a cam roll. The sequence of cams can be changed to produce various weave patterns; change in weave patterns can also be produced for any particular cam roll by varying the sequence of shedding and indexing motion. A small amount of triaxial fabric samples were woven from this loom with 3 ply 840 denier nylon yarn, and a sequence of biaxial fabrics woven from the same yarn was evaluated for various structures and mechanical properties. The stability of triaxial fabric is much greater than the biaxial fabric with same percent open-area. The triaxial fabric exhibits greater isotropy in its bending behavior and a greater shear resistance than a comparable biaxial fabric (4,5).

The most recent study of triaxially woven structure was carried out by a group of Japanese textile researchers at Kyoto University. The study concerned the specific tensile strength of triaxial fabric by making the tensile testing as a function of direction for the triaxial fabric with 48 yarns made by a braiding machine.

CHAPTER II

MATERIALS AND PROCEDURES OF PHYSICAL TESTING PROGRAM

Materials

In order to compare the properties of the triaxial fabric with those of comparable biaxial fabrics, four different biaxial fabrics were woven. The constructional details of triaxial fabric and comparable biaxial fabrics are given in Table 1. The structure of triaxial fabric is shown in Figure 2. The structure of biaxial fabrics is shown in Figure 3.

Table 1. Constructional Details of Fabrics

Fabrics	Triaxial Fabric	Biaxial Fabric Samples			
		No. I	No. II	No. III	No. IV
Construction	---	1/1 Plain	1/2 45 RH Twill	1/1 Plain	1/2 45 RH Twill
Ends/ in	32x32	31	31	49	49
Picks/in	32	33	33	50	49
Warp Yarn Count (Den.)	280x280	220/2 (440)	220/2 (440)	220	220
Filling Yarn Count (Den.)	220	220/2 (440)	220/2 (440)	280	280
Fabric Weight (oz/sq. yd.)	3.6	3.9	3.8	3.5	3.3

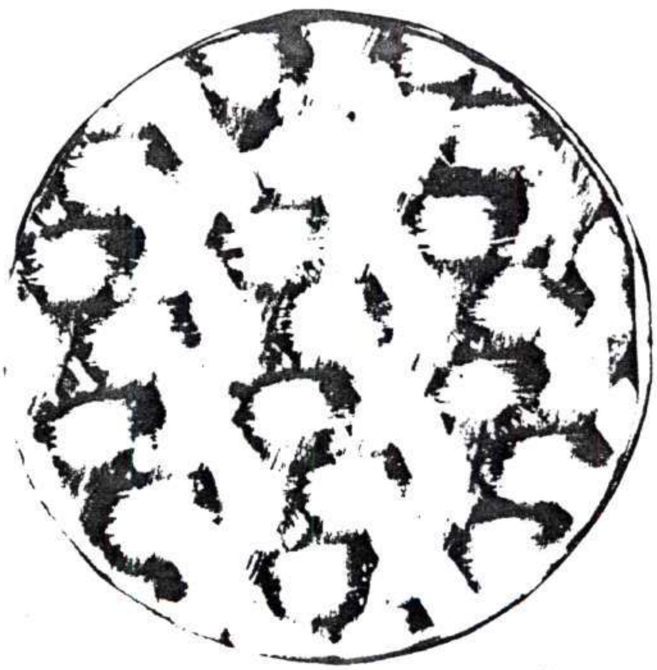


Figure 1. Triaxial Fabric

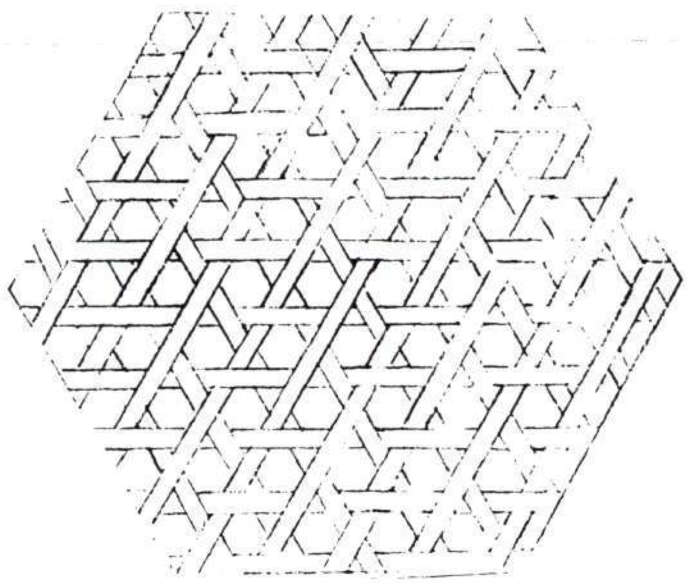
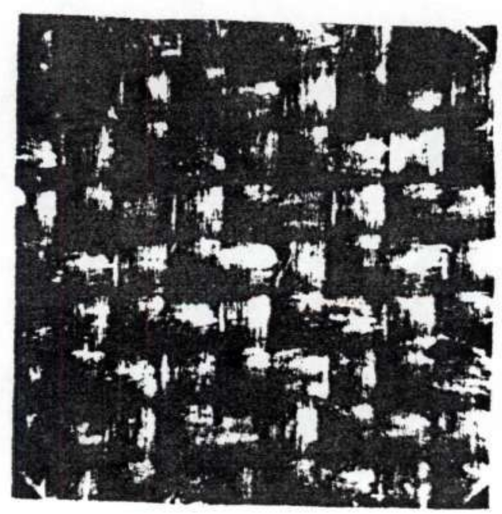


Figure 2. Structure of Triaxial Fabric

Fabric No.1

Fabric No.2

Fabric No.3



Fabric No.4

Figure 3. The Comparable Biaxial Fabrics

The triaxial fabric supplied by Doweave Inc. was approximately 17 inches wide by 110 inches long. In this fabric, both sets of warps are interlaced by the filling only. Each warp yarn goes on top of the other two sets of yarns for two picks and then goes under the filling but on top of the other set of warp for two picks. There is no interlacing between two sets of warp yarns in this fabric, as shown in Figure 2.

The biaxial fabric No. I was designed to have the same fabric weight and thread per inch width in both warp and filling directions, as the triaxial fabric with a short float length weave. Fabric No. II was designed to have the same fabric weight and thread per inch width in both warp and filling direction as the triaxial fabric with a moderate float length weave. Fabric No. III was designed to have the same fabric weight and yarn count as the triaxial fabric with a short float length weave. Fabric No. IV was designed to have the same fabric weight and yarn count as the triaxial fabric with a moderate float length weave.

All four biaxial fabrics were woven on a dobby loom with a fractional let oof motion. The fabrics measured roughly 30 inches wide by 180 inches long. The warp yarn in fabrics No. III and No. IV was sized with Elvanol T-25, a water soluble polyvinyl alcohol. The fabrics were scoured using hot water and a mild detergent before testing.

Procedures of Physical Testing Program

In order to clearly demonstrate the relative merits of triaxial fabric, the following properties were determined for each fabric and the properties of triaxial fabric were compared to those comparable biaxial fabrics

(1) Fabric Construction

The yarn per inch width in each of the principal directions and the fabric weight and thickness were measured. The orientation and parallelism of the three sets of yarns in triaxial fabric were checked. The density of the fabric was calculated from the thickness and weight measurements.

(2) Yarn Crimps

The percent crimp in the yarns in each of the principal directions was determined by measuring the difference in distance between two points on the yarn as it lies in the fabric and the same two points when the yarn has been removed from the fabric and straightened.

(3) Permeability and Porosity

The permeability of the fabrics was determined by using the Frazier Air Permeability Machine (ASTM D 737-69) with the pressure difference between fabric surfaces at 0.5 inch of water. Porosity was determined by measuring the percent light transmission through the fabric with a Beckman Spectrophotometer. The measurements were taken under the visibli light, with a weave length range of 300μ - 700μ.

(4) Shear Stiffness

The shear stiffness was measured here by using an apparatus as shown in Figure 4. A specimen 8 inches long and 12 inches wide was held in a fixed clamp at AB along the line of threads and the lower movable clamp CD (weight 704.8 grams). During experiment, a side way force is applied to draw the lower movable clamp to one side and to set up within

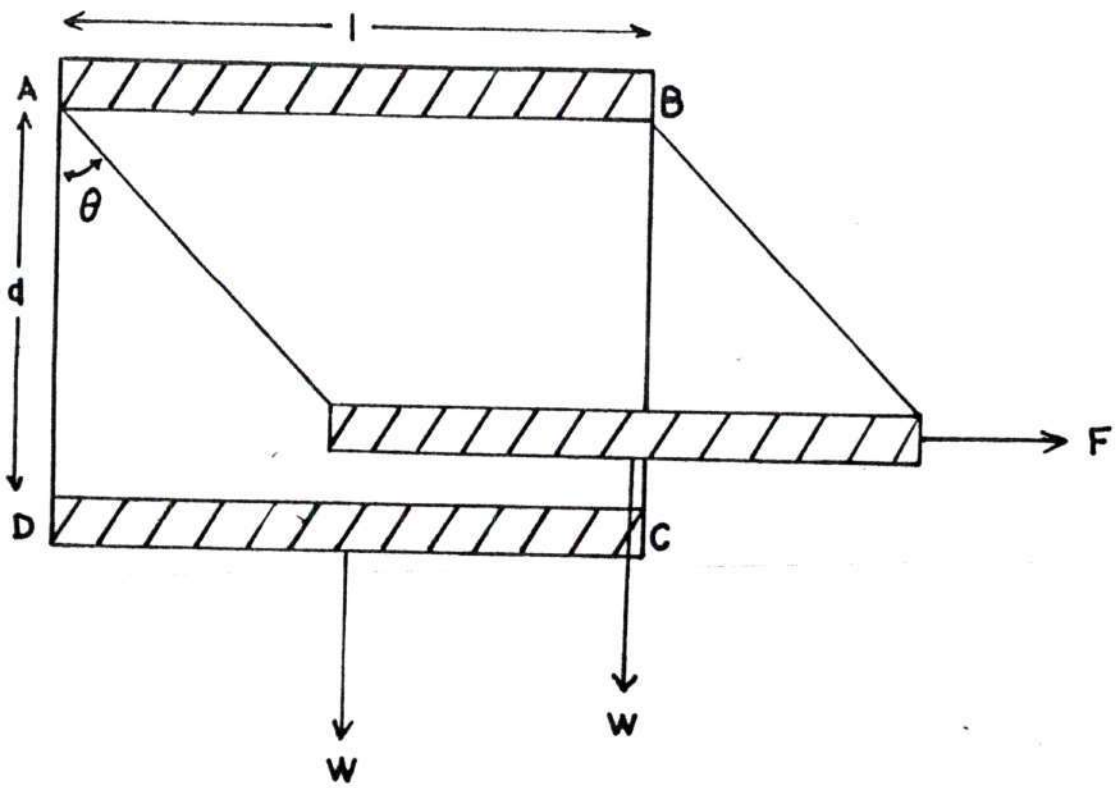


Figure 4. Principle of Fabric Shear Test

and in the direction perpendicular to the machine direction and three different loads (W) were used (704.8 grams, 1204.8 grams, 1704.8 grams).

(5) Bending Stiffness

The bending stiffness of the biaxial fabrics was determined in 0°, 30°, 60°, and 90° from filling (measured anti-clockwise). The triaxial fabric was determined in 0°, 30°, 60°, 90°, 120°, and 150° to filling. All tests were conducted by using the Cantilever Test (ASTM D 1388-64, option A).

(6) Tensile Properties

The fabrics were tensile tested in each of the principal directions and various off principal directions as listed in Table 2, in order to demonstrate the isotropy of fabric. The rupture load, rupture elongation and modulus were measured. The detailed tensil testing program is given in Table 2. In this experiment all specimens were tested by using the Instron machine (ASTM 1682-64 Instron CRE).

Slippage in the jaws always occurred when high strength materials were tested. In order to prevent this during our experiment, certain modifications on the jaw faces and specimen were necessary. The jaw faces were taped with masking tape to increase the surface friction and to act as a cushion to decrease the edge effect. All specimens were also taped with masking tape under the jaw face area except those with one inch gage length which were coated with epoxy.

(7) Tearing Strength

The tearing strength of the fabrics was determined in the principal directions with two specimens each by the tongue (single rip) method

Table 2. The Detailed Tensile Testing Program

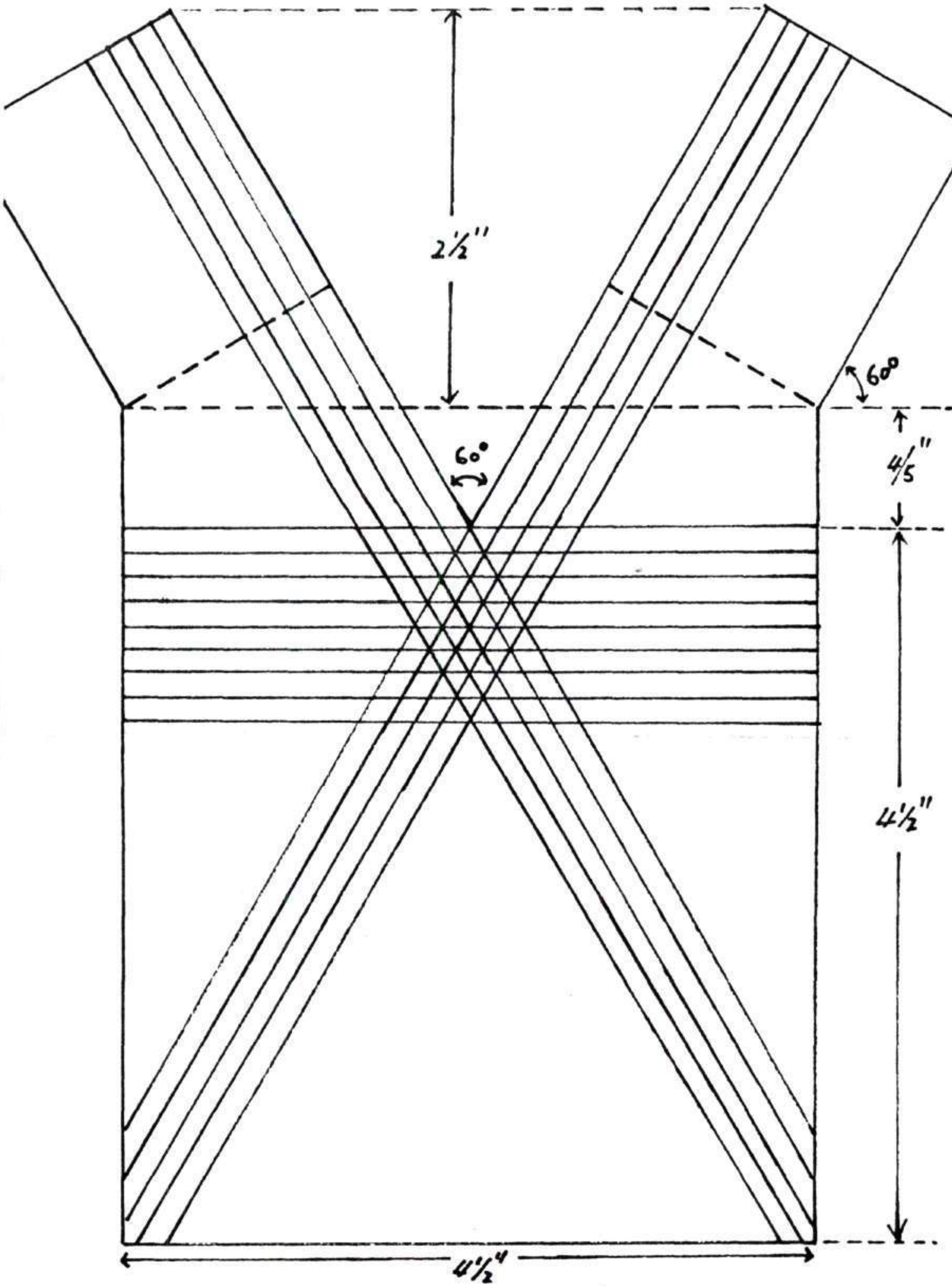
	Specimen Size within the gage (1) (width x length)	Test Directions (2)	Strain Rate	Sample Size
Group (1) Constant width	1" x 3" 1" x 5"	Biaxial 0°,30°,60°, 90° Triaxial 0°, 30°,60°,90°, 120°,150°	66% 100%	5 5
Group (2) Narrow width	1/2" x 1" 1/2" x 3" 1/2" x 5"	Biaxial 0°,30°,60°, 90° Triaxial 0°, 30°,60°,90°, 120°,150°	100% 66% 100%	5 5 5
Group (3) Wide width	3" x 3"	Biaxial 0°,30°,60°, 90° Triaxial 0°, 30°,60°,90°, 120°,150°	66%	5

(1) Measurement specimen width x length span between jaw.
(2) Measurement anti-clockwise from the filling.

specimen could not give satisfactory results from triaxial fabric because there were only few through-going-yarns being clamped in the jaws. Thus, the dimensions of the specimen were modified in order to let the through-going-yarn be parallel to the tongue and be clamped properly. The modified specimens are shown in Figure 5 in actual size.

(8) Ball Burst Strength

The bursting strength from the fabrics at rupture was measured



2½"
60°
60°
4/5"
4½"
4½"

CHAPTER III

RESULTS AND DISCUSSIONS

(1) Fabric Thickness and Density (See Table 3)

Table 3. Thickness and Density of Fabrics

	Triaxial Fabric	Biaxial Fabrics No.1	No.2	No.3	No.4
Fabric Thickness (In.)	0.01	0.0085	0.0095	0.008	0.008
Fabric Density	0.48	0.61	0.53	0.57	0.55

(2) Yarn Crimp

Yarn crimp in fabrics is shown in Table 4.

Table 4. Yarn Crimp in Fabrics

	Triaxial Fabrics	Biaxial Fabrics No.1	No.2	No.3	No.4
Warp Yarn Crimp	0.9%	1.25%	1.05%	2.5%	1.5%
Filling Yarn Crimp	3%	0.8%	0.7%	2.3%	1%

Warp has more crimp than

(3) Permeability and Porosity

The permeability and porosity of fabrics are shown in Table 5.

Table 5. Permeability and Porosity of Fabrics

Fabrics	Triaxial Fabrics	Biaxial Fabrics No. 1	Biaxial Fabrics No. 2	Biaxial Fabrics No. 3	Biaxial Fabrics No. 4
Air Permeability ($Ft^3/ft^2/min$)	113	70	96	28	58
Porosity (percent light transmission)	2%	3%	1.5%	2%	1%

The biaxial fabrics No. 2 and No. 4 have lower porosity but higher permeability than fabrics No. 1 and No. 3 respectively. This is due to the fact that the longer float yarn in the twill fabrics No. 2 and No. 4 tends to flatten out and cover more area which decreases the porosity of the fabric. On the other hand, the twill structure of fabrics No. 2 and No. 4 provides oblique paths between yarns for air to flow through.

The triaxial fabric has the highest permeability among all fabrics with only two percent light transmission. This is because in the triaxial fabric, both sets of warp are interlaced with fillings only. This gives a loosely constructed fabric with a long float length warp; therefore, the air can permeate easily by following the oblique paths in the fabric but the light is blocked by the flattened yarns.

(4) Shear Stiffness

Results are given in Figures 6-11, which show the variations of

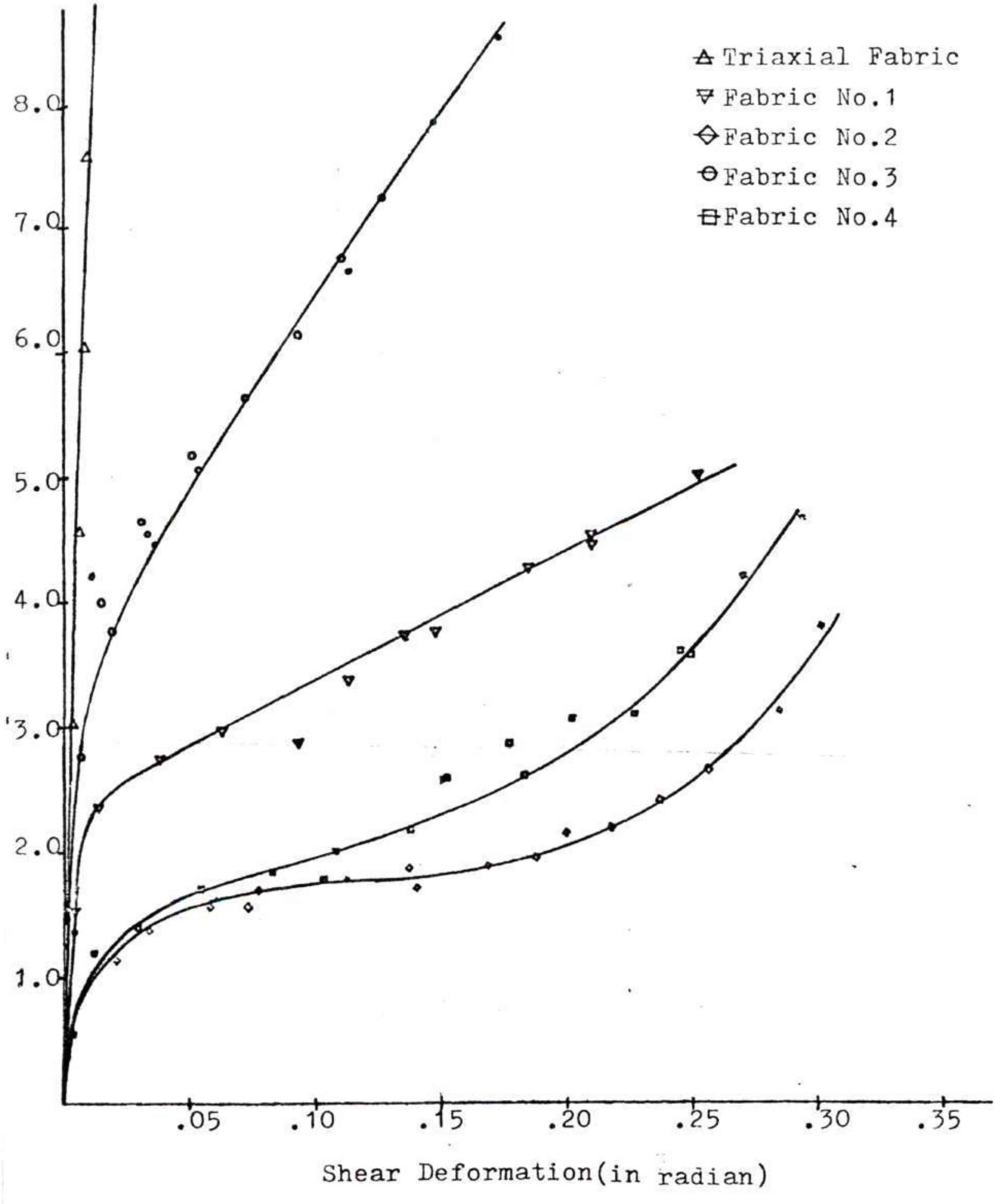


Figure 6. Shear Couple Per Unit Area Of Various Fabrics (Warp Perpendicular to Shear Force,W=1704.8GM.)

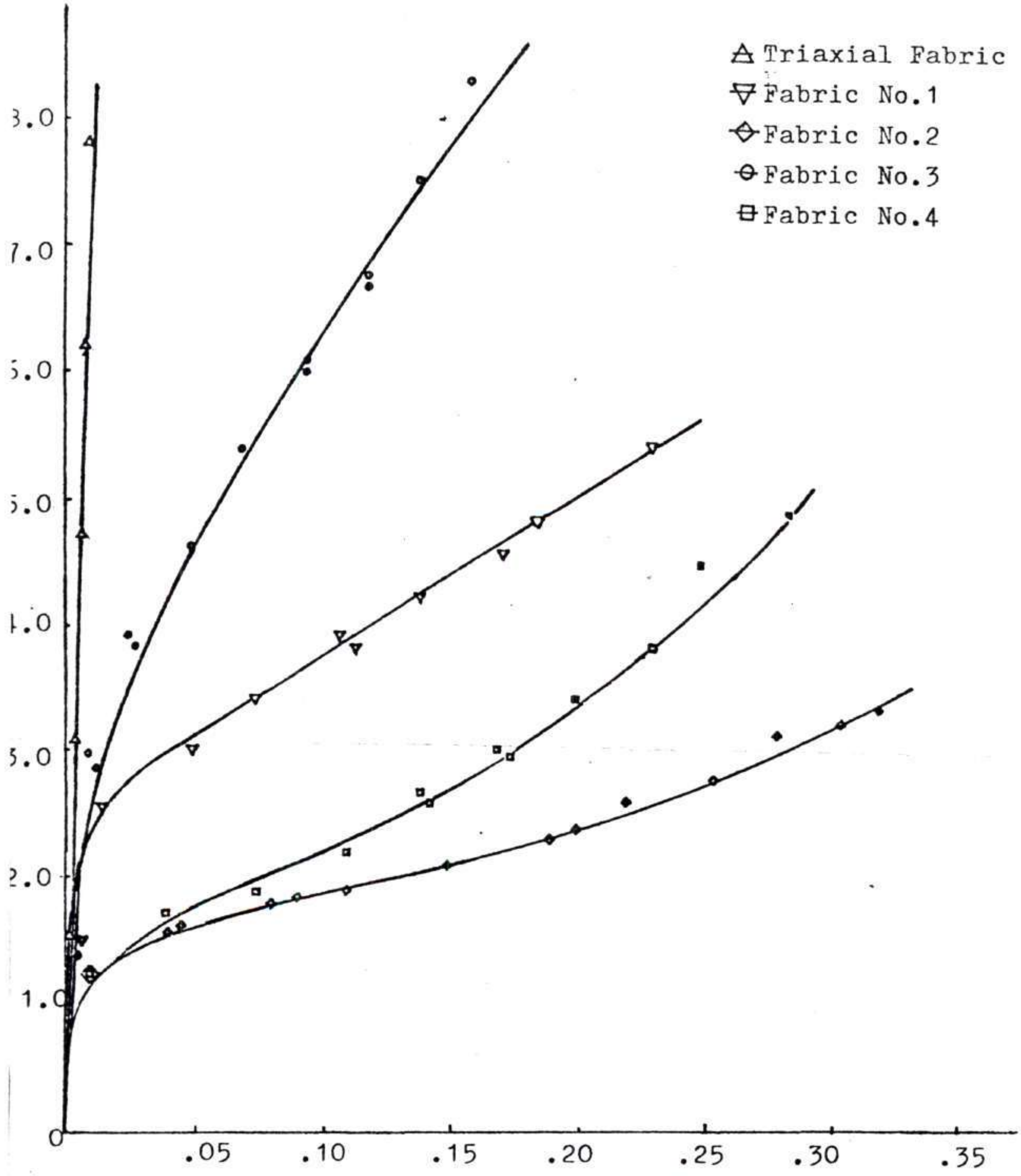


Figure 7. Shear Couple Per Unit Area of Various Fabrics
(Warp Perpendicular to Shear Force W-1204 8GM)

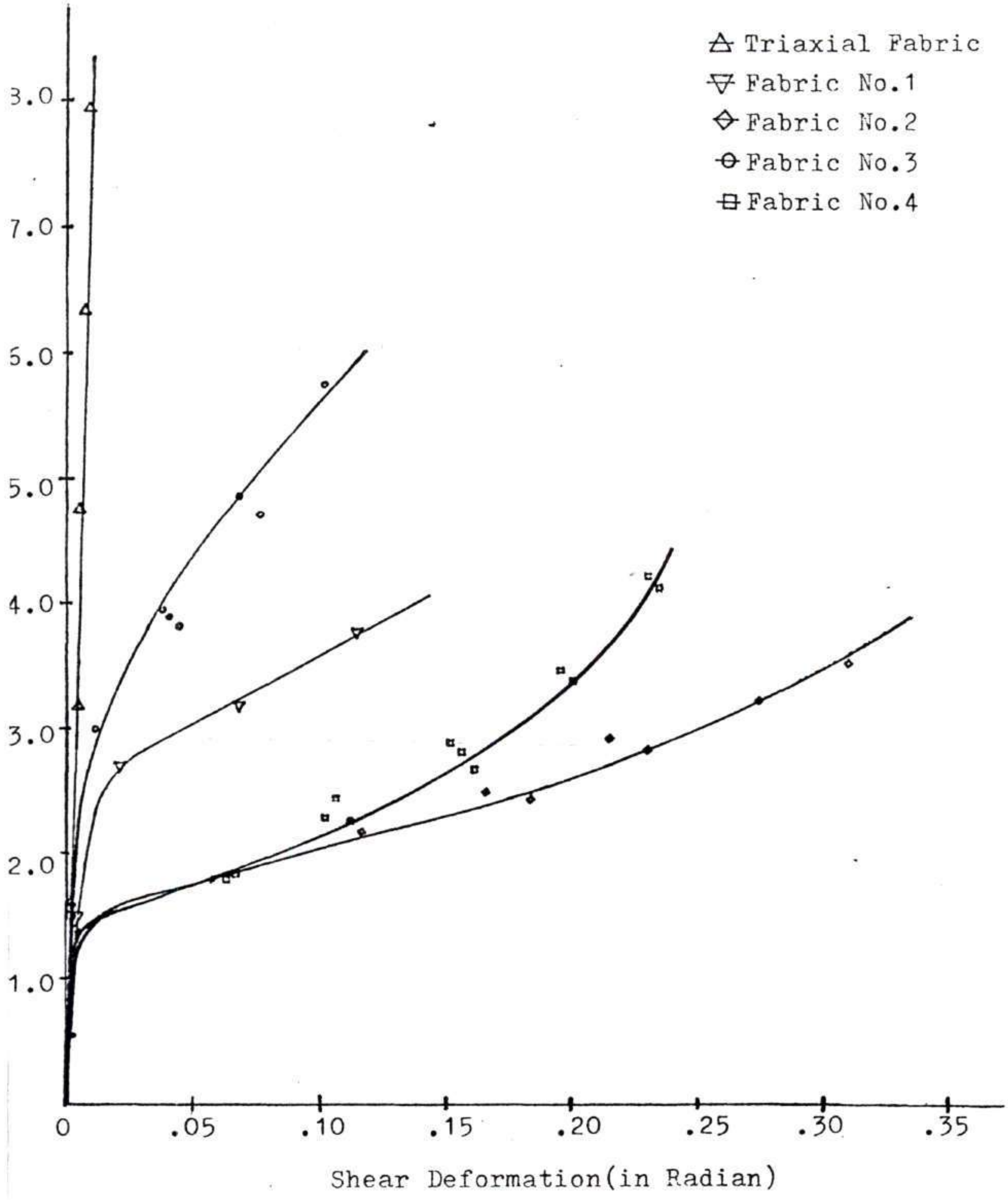


Figure 8. Shear Couple Per Unit Area of Various Fabrics
(Warp Perpendicular to Shear Force W-704 8GM)

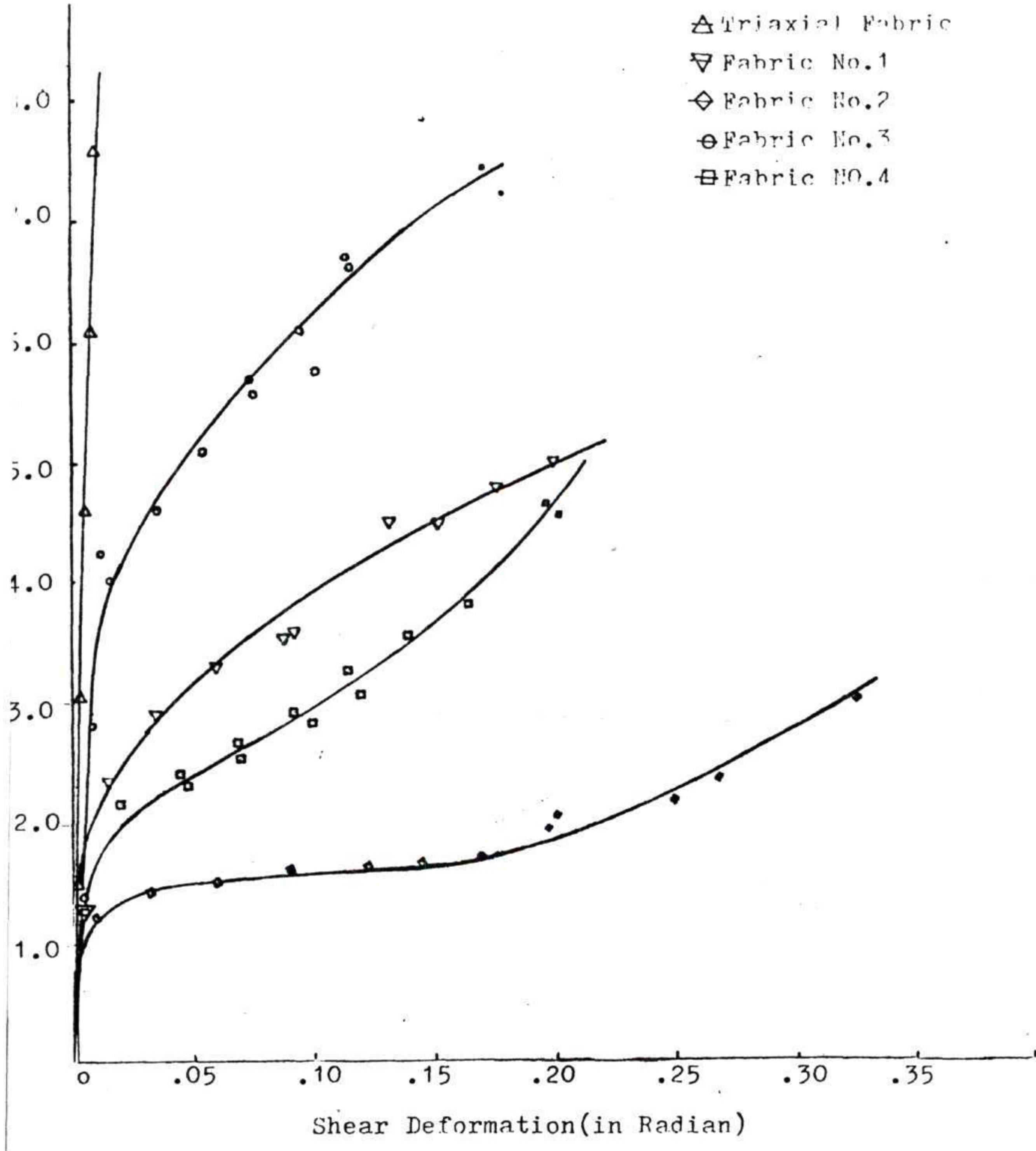


Figure 9. Shear Couple Per Unit Area of Various Fabrics
(Filling Perpendicular To shear Force,W=1704.8GM.)

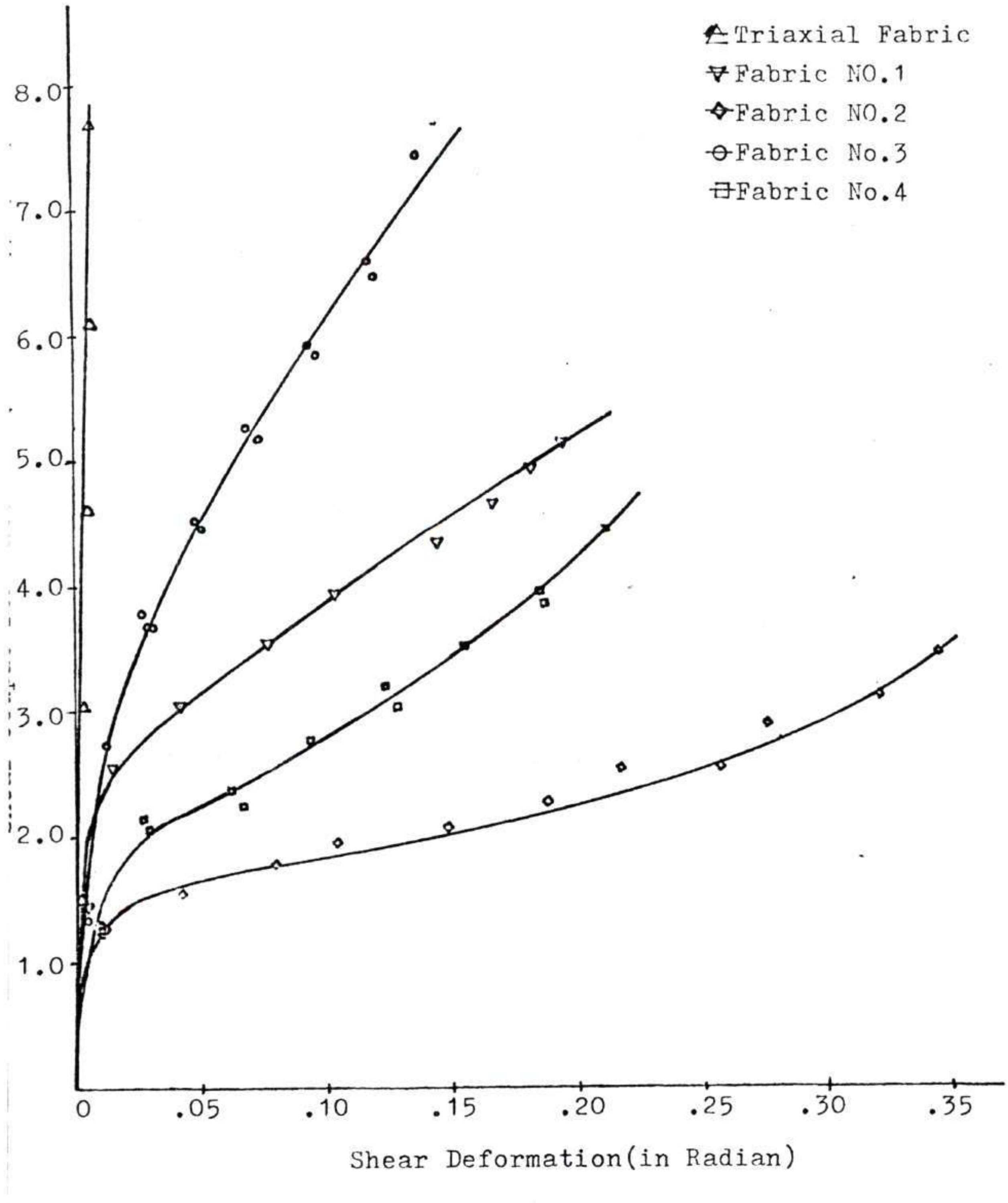


Figure 10. Shear Couple Per Unit Area of Various Fabrics
(Filling Perpendicular to Shear Force,W=1204.8GM)

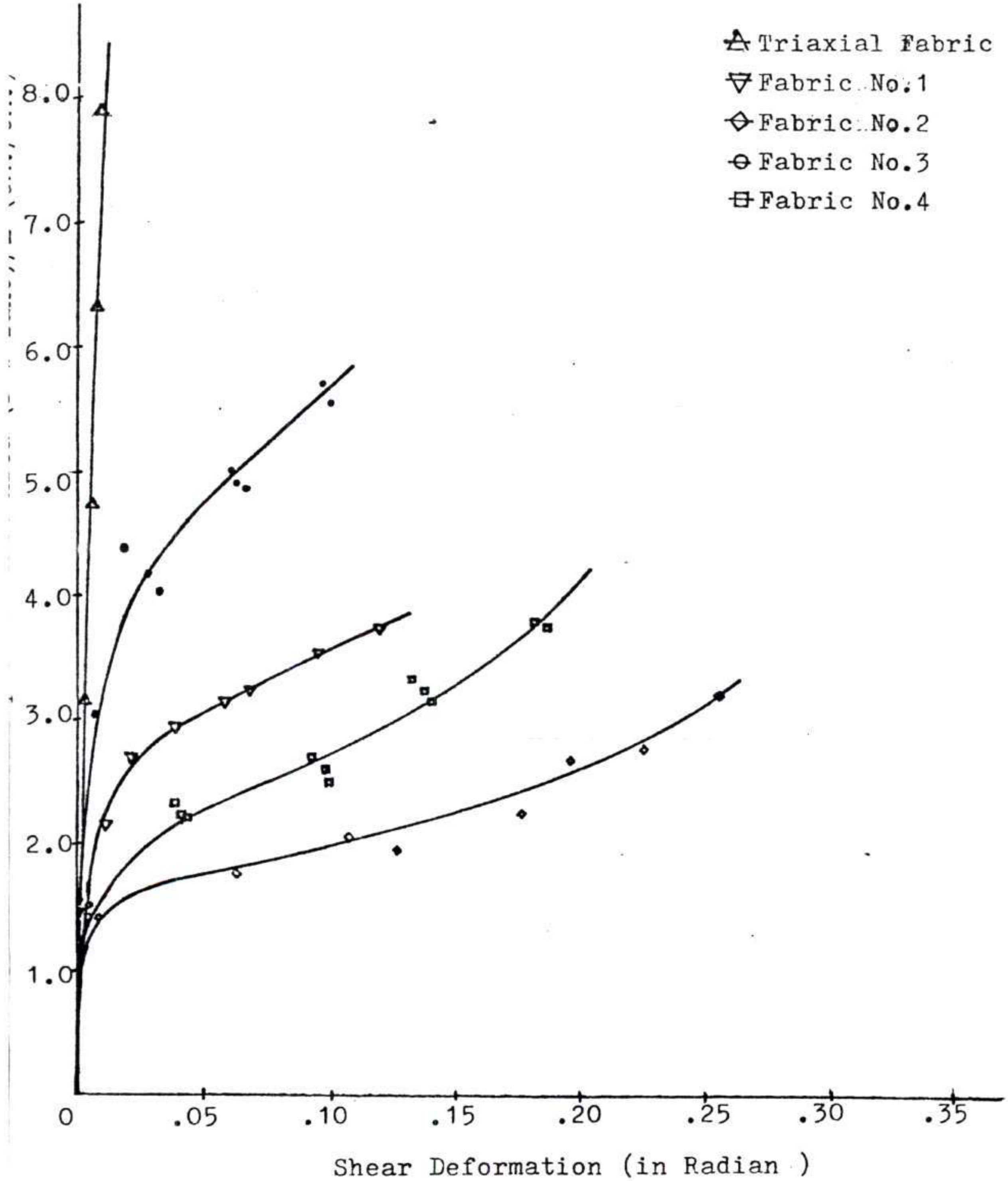


Figure 11. Shear Couple Per Unit Area of Various Fabrics
(Filling Perpendicular to Shear Force W-704 8CM)

couple per unit area of the fabric is determined as follows:

If the fabric has zero resistance to shear, the magnitude of the force F_o is given by:

$$F - W \operatorname{Tan}\theta$$

(See the arrangement in Figure 4)

If the fabric has resistance to shear deformation, an additional force is required. If total force is F, then:

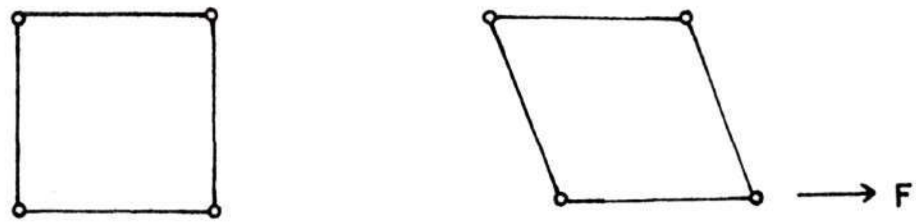
$$F - F_o = F - W \operatorname{Tan}\theta$$

and shear couple is $(F - W \operatorname{Tan}\theta)d$.

Then the shear couple per unit area C is

$$(F - W \operatorname{Tan}\theta)d/ld = (F - W \operatorname{Tan}\theta)/l$$

The shear couple per unit area of triaxial fabric is substantially greater than that for comparable biaxial fabrics. This can be explained by considering that the triaxial and biaxial fabrics consist in essence of pin joint, triangular, and rectangular trellises, respectively, as shown in Figure 12. As the shearing action takes place on those two different configurations, the pin joint rectangle tends to change its configuration in plane as long as the shear force is greater than the frictional force at the joints. The pin joint triangle would not be able to change its configuration in plane but will buckle out of plane as the shear force builds up. Thus, the triaxial fabric always yields a very high shear couple per unit area before buckling.



(a)

(b)

why not like

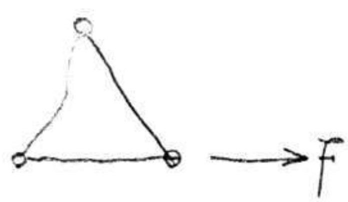
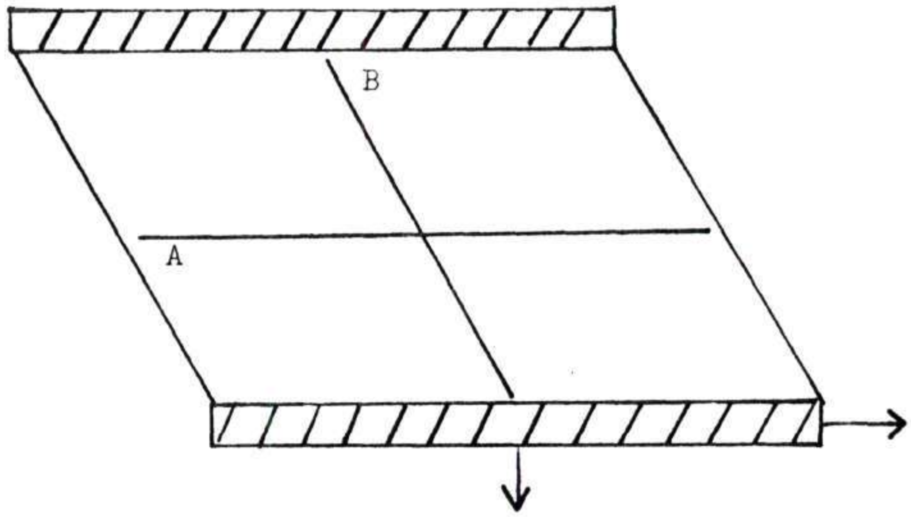


Figure 12. Shear of (a) Pin Joint Rectangle
(b) Pin Joint Triangle

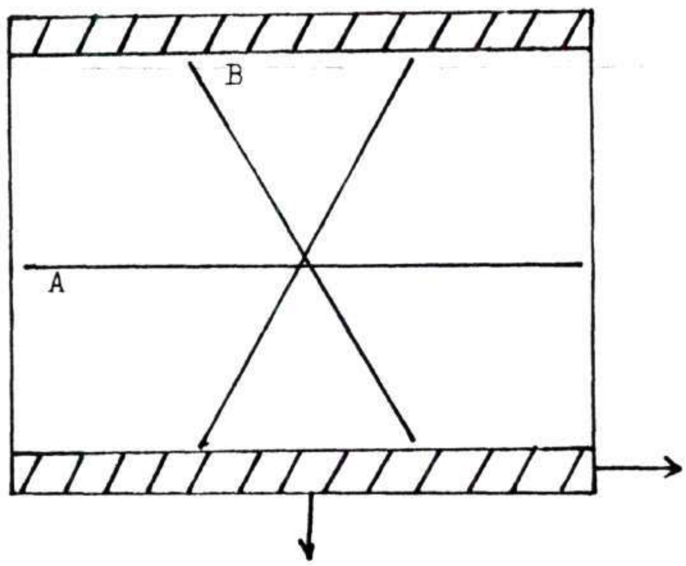
is observed during experiment. At the beginning of the experiment, two sets of yarns A and B in the triaxial fabric were in a condition similar to the yarns A' and B' in the biaxial fabrics at large deformation as shown in Figure 13. In addition, the third set of yarn C of triaxial fabric suffered a buckling deformation because the contraction of the fabric is in the direction of the third set of yarns. In triaxial fabrics, the buckling started at the left hand corner and then extending rapidly over the whole fabric surface.

Among the biaxial fabrics, the shear couple per unit area of fabrics No. 2 and No. 4 is much lower than fabrics No. 1 and No. 3, because fabrics No. 2 and No. 4 have a moderate float weave which means fewer yarn crossover points with more freedom of movements than the tight plain structures in fabrics No. 1 and No. 3. Fabric No. 3 has a higher shear couple per unit area than any other biaxial fabric as a result of tight plain construction.

The shear behavior of biaxial fabrics can be explained in three steps. Start from a point where there is no deformation in the fabric; the free going yarns AB are at its original position as shown in Figure 14a. A shear force now is applied; the bending deformation of the free going yarns AB between the crossover points is without rotational slippage as shown in Figure 14b. As the shear force increases, it soon overcomes the maximum inter-yarn frictional force and the free going yarns AB start to bend and to rotate at crossover points as shown in Figure 14c. This occurs at point A on a typical shear curve as shown in Figure 15. Further increases in shear resistance are caused by the in-



(a)



(b)

Figure 13 Shear of (a) Biaxial Fabric

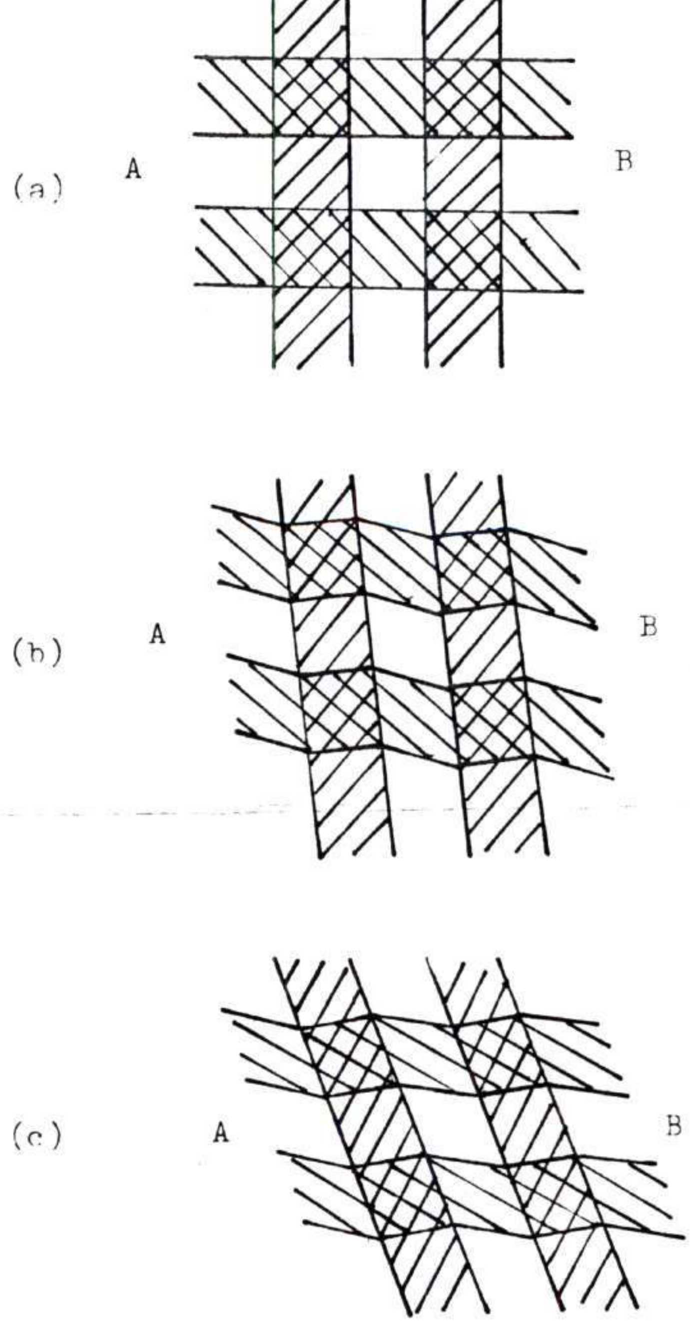


Figure 14. The Yarn Bending Deformation in Biaxial Fabric Shear

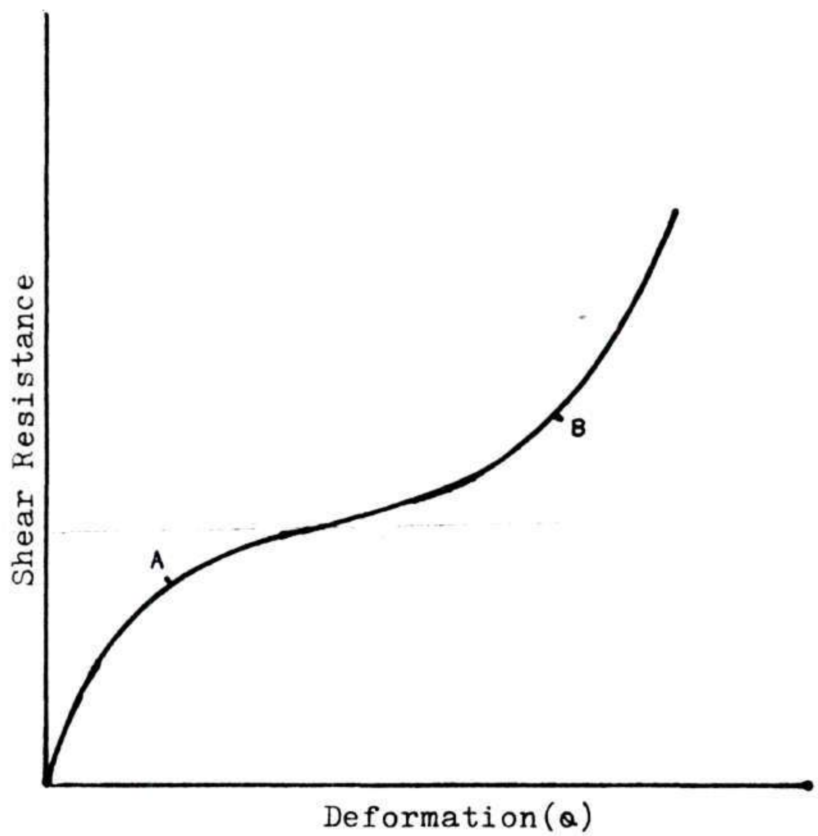


Figure 15. A Typical Shear Curve

points until the fabric jamps. This occurs at point B on the curve in Figure 15. From here on, the shear resistance will pick up rapidly until the fabric buckles.

In the biaxial fabrics, the buckling started in the left hand corner (see arrangement in Figure 4) and then appeared at the bottom right hand corner, finally extending gradually over the whole fabric surface.

(5) Bending Stiffness

The results are given in Table 6 and a polar variation of flexural rigidity for the fabrics is shown in Figure 16.

All the biaxial fabrics are stiffest in warp direction with filling somewhat less stiff. This is probably because the filling yarns are flattened out in the fabrics. When tested in other than principal directions, the stiffness is much less than in the principal directions.

Table 6. The Flexural Rigidity of the Fabrics

	Direction	Triaxial Fabric	Biaxial Fabrics No.1	No.2	No.3	No.4
	0°	166	556	356	514	355
	30°	164	363	244	300	195
Flexural	60°	177	407	300	332	270
Rigidity	90°	131	568	566	618	652
(mg - cm)	120°	167				
	150°	163				

The bending stiffness is lowest in biaxial fabrics when tested in the direction 30° to the filling (measured anti-clockwise). In this direction, the less stiff filling yarns are in a longer path, 30° to

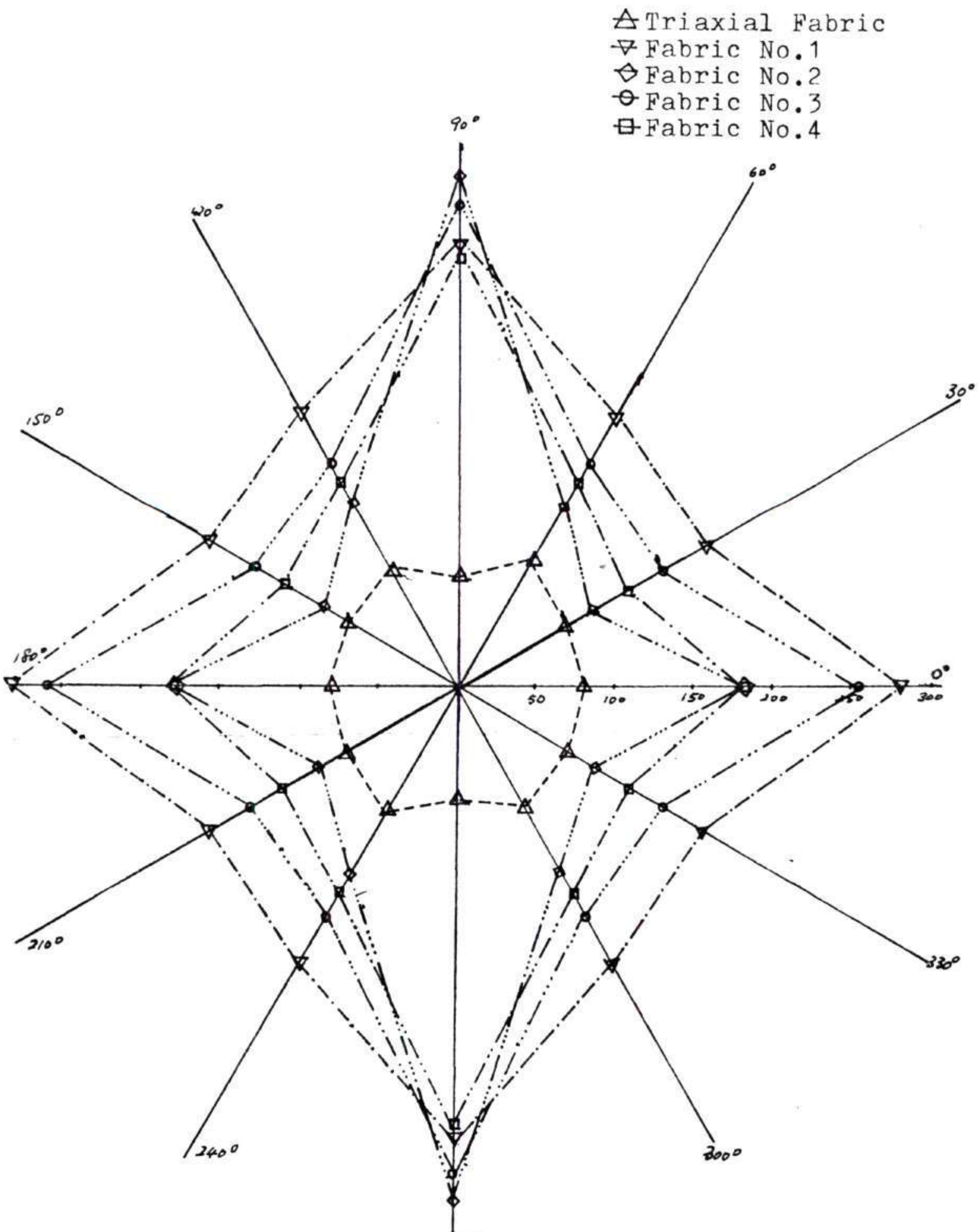


Figure 16. Polar Variation of Flexural Rigidity for Various Fabrics (MG.-CM.)

bending direction, and bear the most load.

In biaxial fabrics No. 1 and No. 3, the variation of stiffness with orientation is not too great, but in fabrics No. 2 and No. 4, a comparable low stiffness is obtained when tested in other than principal directions. The fact is that normally friction is a major component of the fabric stiffness when tested in other than principal directions and most friction is caused by the yarn crossover points. The plain woven fabrics No. 1 and No. 3 have two-third more yarn crossover points than the equivalent 1/2 twill woven fabrics No. 2 and No. 4 respectively. Thus, the fabrics No. 1 and No. 3 are stiffer than fabrics No. 2 and No. 4, respectively, when tested in other than principal directions.

In triaxial fabric, there is almost no variation of stiffness with orientation due to its advantage of having three sets of yarns in the fabric. These isotropic properties are clearly shown in Figure 16.

(6) Tensile Properties

The results are given in Tables 7-11. The rupture load and elongation of triaxial fabric are compared to those comparable biaxial fabrics in various directions which are plotted on a polar graph as shown in Figures 17-28.

In both principal direction, biaxial fabrics No. 1 and No. 2 yield the highest rupture load as the result of having the highest denier per inch width when measured in both warp and filling directions. The other two biaxial fabrics No. 3 and No. 4 are woven from the same yarns which are being used in triaxial fabric. The warp yarns in the triaxial fabric are used as fillings, and fillings as warps in fabri No. 3 and No. 4. In both principal directions, fabrics No. 3 and

Table 7. Tensile Properties of Triaxial Fabri

	SP. size	0°	30°	60°	90°	120°	150°
Rupture load (lb./in.Width)	3"x3"	99	60	131	45	131	61
	1"x3"	97	---	123	0.51	120	----
	1"x5"	96	---	120	---	125	----
	½"x1"	98	---	127	0.05	125	----
	½"x3"	97	---	124	---	125	----
	½"x5"	91	---	128	---	121	----
Rupture Elongation (%)	3"x3"	14.5%	17.5%	17%	.18%	17%	18%
	1"x3"	16%	-----	15%		14%	----
	1"x5"	14%	----	13.5%	----	13.5%	----
	½"x1"	18%	----	19.5%	12%	18%	---
	½"x3"	15%	----	15%	----	16%	----
	½"x5"	13%	----	14%	----	14%	----
MOdulus (lb./in.Width)	3"x3"	820	421	1092	265	1096	451
	1"x3"	880	----	1191	15	1156	----
	1"x5"	948	----	1220	----	1220	----
	½"x1"	704	---	994	1.6	838	----
	½"x3"	887	----	1220	----	1176	----
	½"x5"	940	---	1323	----	1261	----
	(wxl)	5-13%	5-13%	5-13%	5-13%	5-13%	5-13%

Table 8. Tensile Properties of Biaxial Fabric No.1

	Specimen size (WXL)	Warp (90°)	Filling (0°)	30°	60°
Rupture Load (lb./in.Width)	3"x 3"	214	236	72	73
	1"x 3"	221	216	11.5	11.8
	1"x 5"	221	237	12.6	10.8
	½"x1"	235	239	1.7	1.7
	½"x3"	226	239	1.8	1.9
	½"x5"	212	224	1.6	1.9
Rupture Elongation (%)	3"x 3"	19%	19%	25%	26%
	1"x 3"	18%	17%	30%	30.5%
	1"x 5"	15.5%	15.4%	27%	29%
	½"x 1"	21.5%	22.6%	28.6%	23%
	½"x 3"	18%	18.8%	25%	25%
	½"x 5"	15%	15.5%	26%	29%
Modulus (lb./in.Width)	3"x 3"	1436	1537	437	440
	1"x 3"	1696	1773	104	109
	1"x 5"	1195	2052	127	125
	½'x 1"	1472	1347	9	11.3
	½"x 3"	1686	1780	13	14
	½"x 5"	1751	2038	11.3	11.6

Table 9. Tensile Properties of Biaxial Fabric No.2

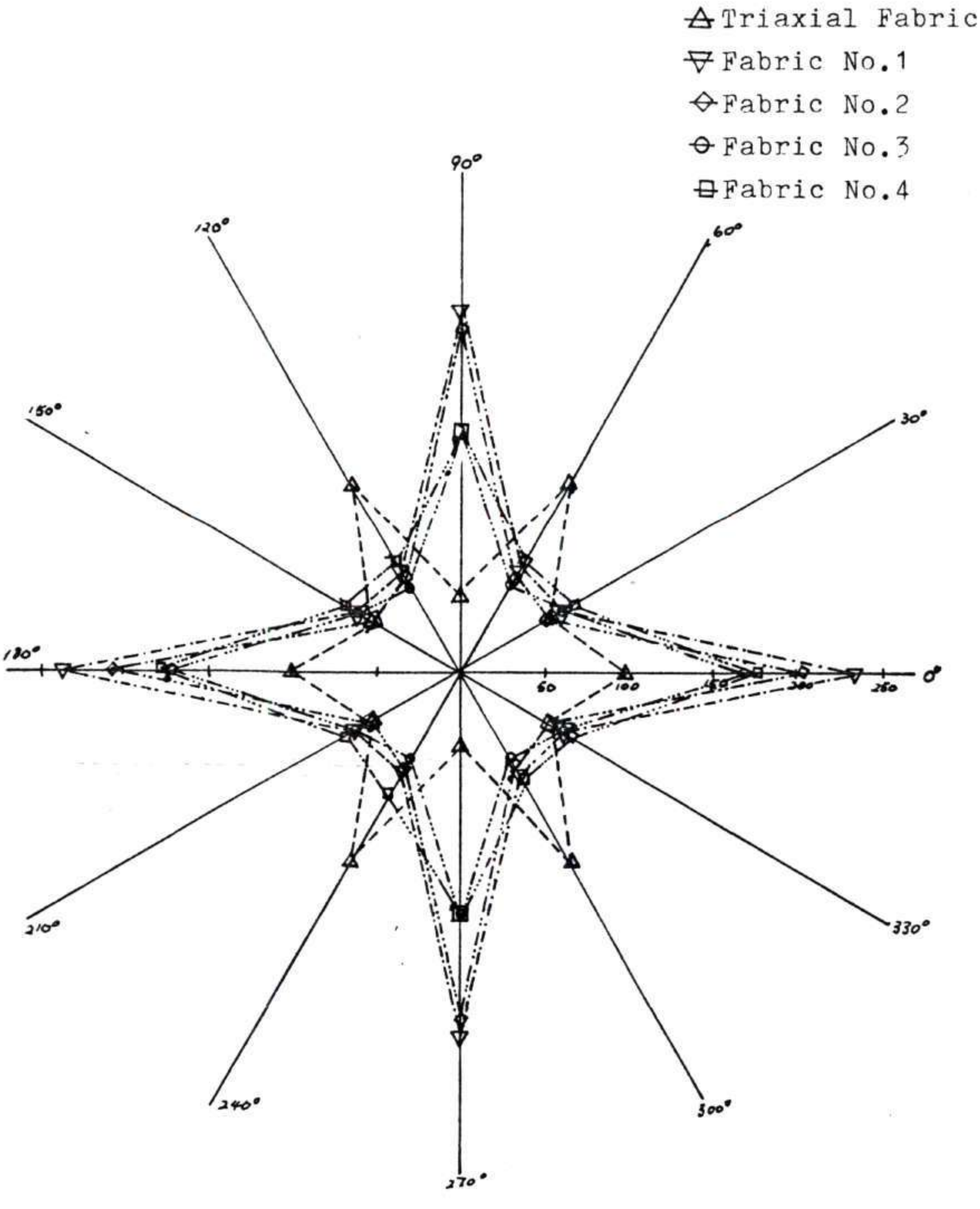
	Specimen size (WXL)	Warp (90°)	Filling (0°)	30°	60°
Rupture Load (lb./in.Width)	3"x 3"	214	212	60	64
	1"x 3"	250	231	2.5	1.5
	1"x 5"	216	229	2	1.4
	½"x1"	235	230	0.32	0.35
	½"x3"	231	210	0.17	0.2
	½"x5"	222	211	0.4	0.3
Rupture Elongation (%)	3"x 3"	17%	18.4%	36.7%	36.5%
	1"x 3"	18%	18.5%	27.3%	32.4%
	1"x 5"	15%	15.5%	29%	31%
	½"x 1"	20.5%	20.3%	29%	25%
	½"x 3"	17.2%	16.2%	25%	24%
	½"x 5"	15%	15%	29%	28%
Modulus (lb./in.Width)	3"x 3"	1612	1518	235	231
	1"x 3"	1788	1697	1	0.75
	1"x 5"	2000	2107	2	1.9
	½'x 1"	1542	1393	0.5	1.9
	½"x 3"	1849	1810	0.35	0.31
	½"x 5"	2042	2000	0.3	0.3

Table 10. Tensile Properties of Biaxial Fabric No.3 .

	Specimen size (WXL)	Warp (90°)	Filling (0°)	30°	60°
Rupture Load (lb./in.Width)	3"x 3"	143	168	68.5	58
	1"x 3"	144	175	65.3	50
	1"x 5"	142	170	63.2	52
	½"x1"	154	177	13	12
	½"x3"	139	160	12	11
	½"x5"	144	164	15	11
Rupture Elongation (%)	3"x 3"	17.3%	18%	26.4%	23.8%
	1"x 3"	15%	16%	40%	39.5%
	1"x 5"	14%	14%	41%	37.4%
	½"x 1"	18.6%	18.3%	32%	27%
	½"x 3"	14.6%	14.4%	30%	29%
	½"x 5"	13.5%	12%	32%	30%
Modulus (lb./in.Width)	3"x 3"	1173	1214	272	267
	1"x 3"	1329	1551	305	256
	1"x 5"	1522	1741	338	299
	½'x 1"	1081	1298	151	143
	½"x 3"	1340	1603	120	105
	½"x 5"	1517	1517	92	61

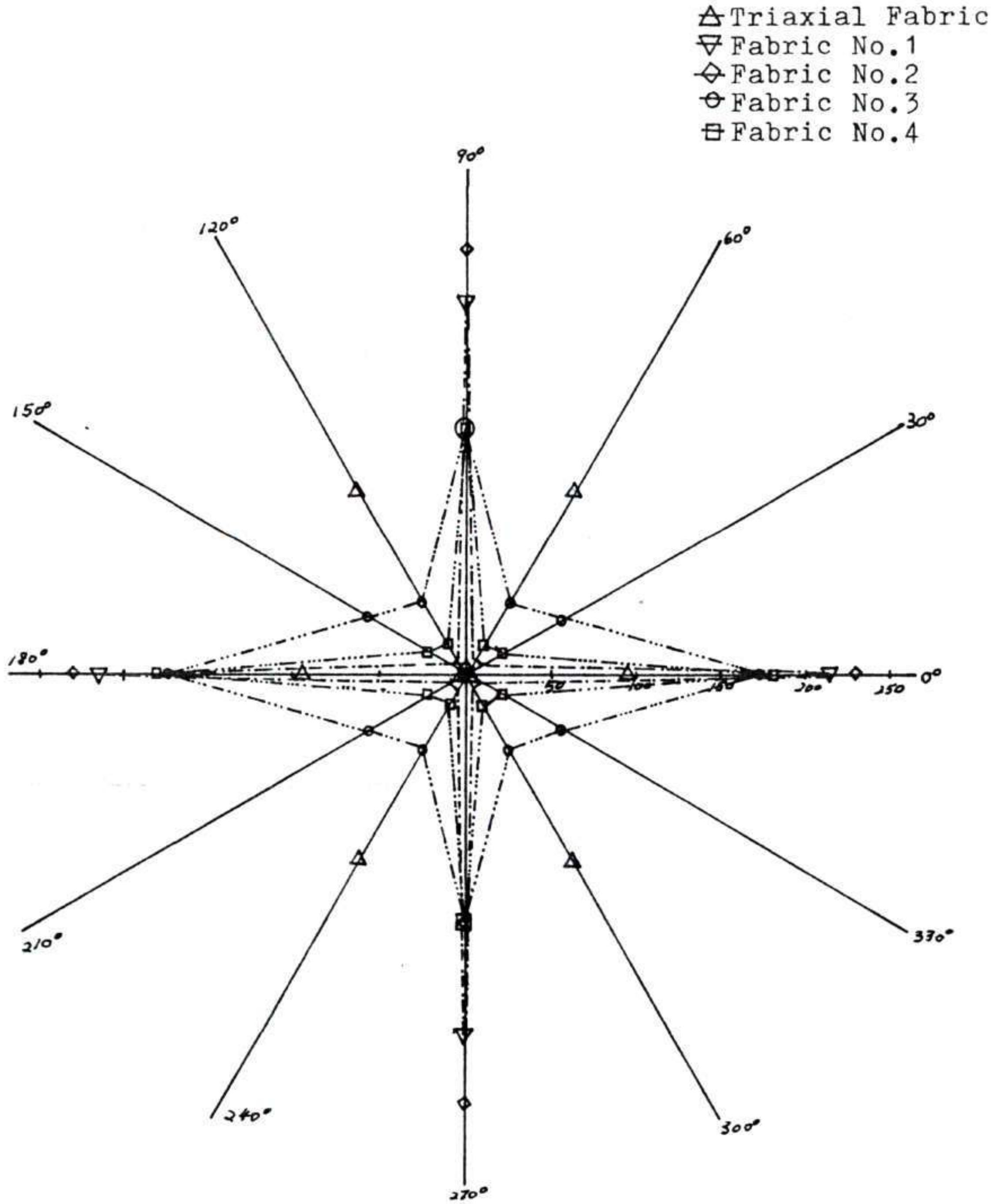
Table 11. Tensile Properties of Biaxial Fabric No.4 .

	Specimen size (WXL)	Warp (90°)	Filling (0°)	30°	60°
Rupture Load (lb./in.Width)	3"x 3"	144	174	75	75
	1"x 3"	142	185	26	22
	1"x 5"	141	175	19	14
	½"x1"	153	179	2.1	2.1
	½"x3"	147	168	2.4	1.6
	½"x5"	131	157	2	1.6
Rupture Elongation (%)	3"x 3"	15.7%	18%	28%	31.3%
	1"x 3"	15%	15%	37%	36%
	1"x 5"	14%	15%	34%	31%
	½"x 1"	19.3%	19.1%	27%	29%
	½"x 3"	17.6%	17%	25%	29%
	½"x 5"	14.75%	13.5%	28%	27%
Modulus (lb./in.Width)	3"x 3"	1183	1277	271	228
	1"x 3"	1236	1436	157	141
	1"x 5"	1317	1732	200	165
	½'x 1"	1145	1178	16	13
	½"x 3"	1194	1333	28	20
	½"x 5"	1144	1421	22.5	21



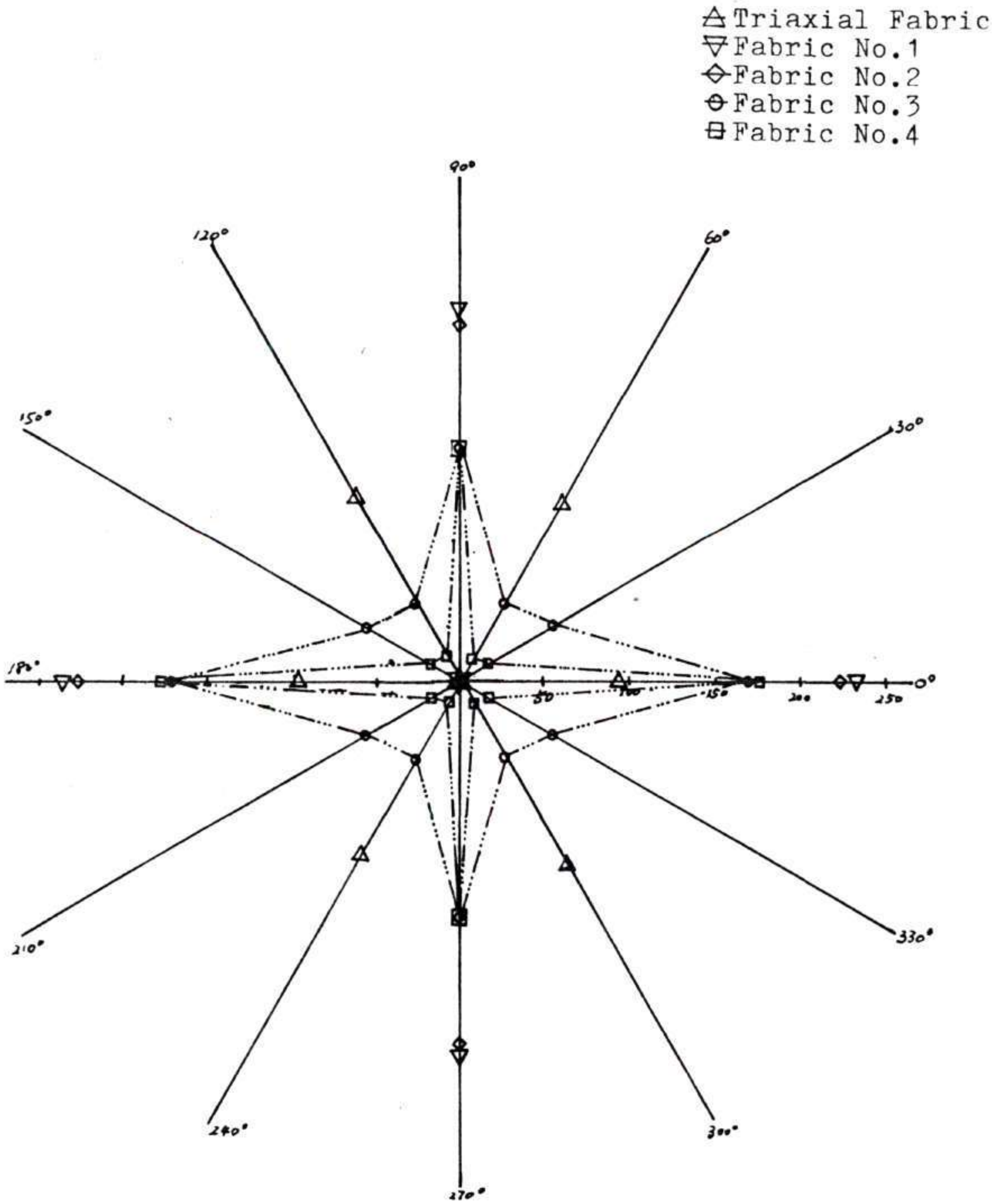
Rupture Load (lb./in.Width)

Figure 17. The Rupture Load of Various Fabrics in Different Direction (With test specimens of three inches wide by three inches long between jaws)



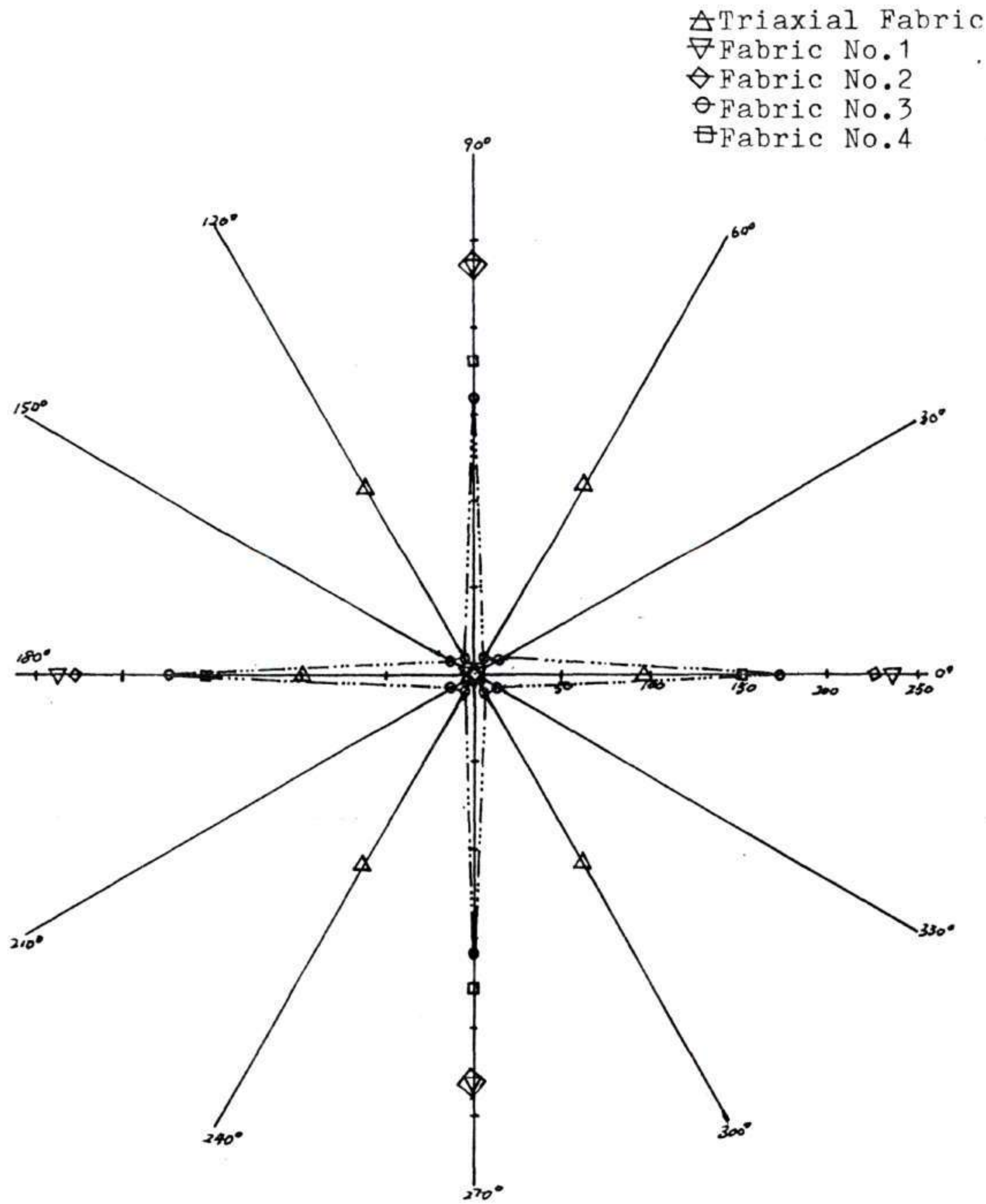
Rupture Load (lb./in.Width)

Figure 18. The Rupture Load of Various Fabrics in Different Direction (With test specimens of one inch wide by three long between jaws)



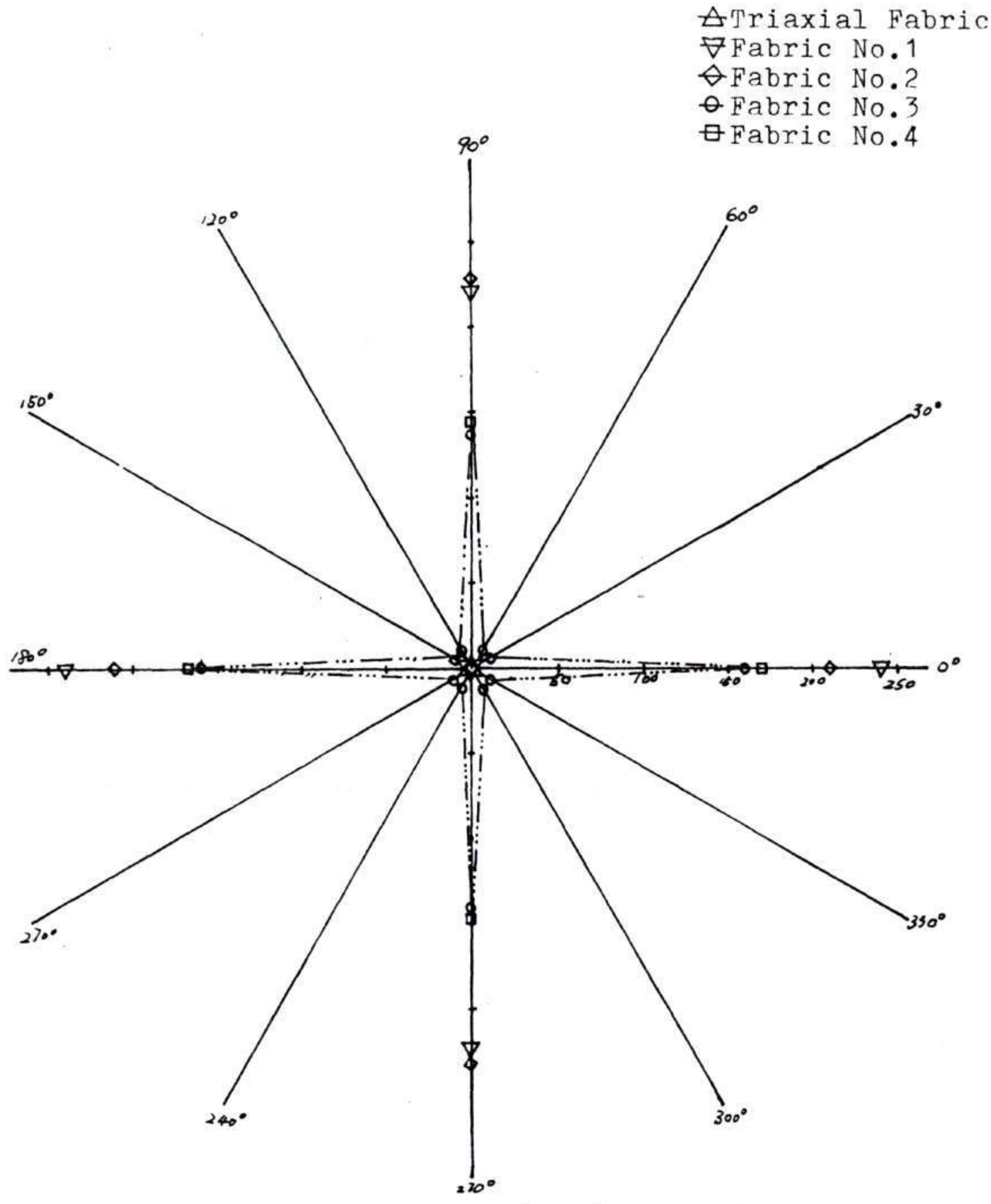
Rupture Load (lb./in.Width)

Figure 19. The Rupture Load of Various Fabrics in Different Directions (With test specimens of one inch wide by five inches long between jaws)



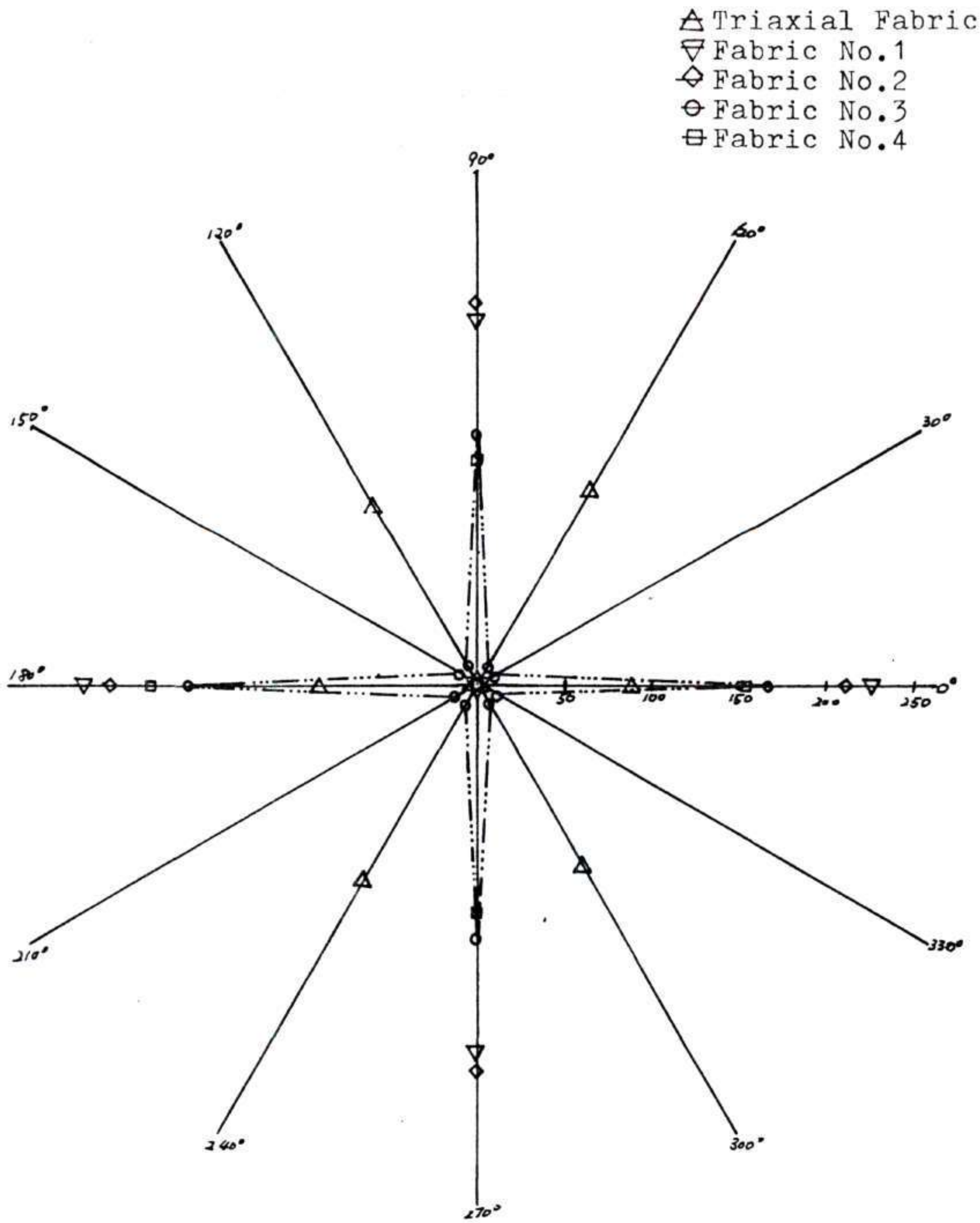
Rupture Load (lb./in.Width)

Figure 20. The Rupture Load of Various Fabrics in Different Directions(With test specimens of half an inch wide by one inch long between jaws)



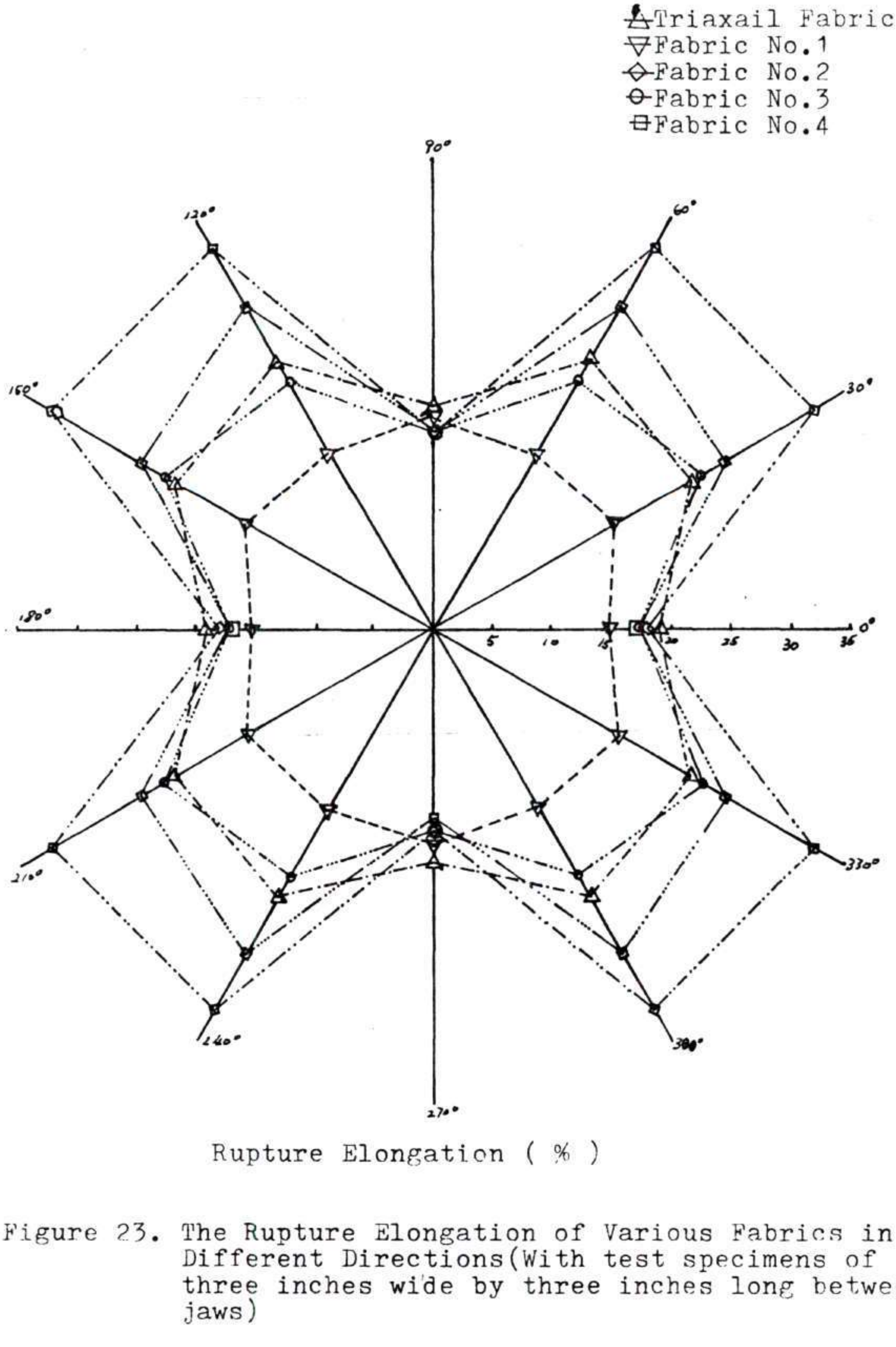
Rupture Load (lb./in.Width)

Figure 21. The Rupture Load of Various Fabrics in Different Directions(With test specimens of half an inch wide by three inches long between jaws)



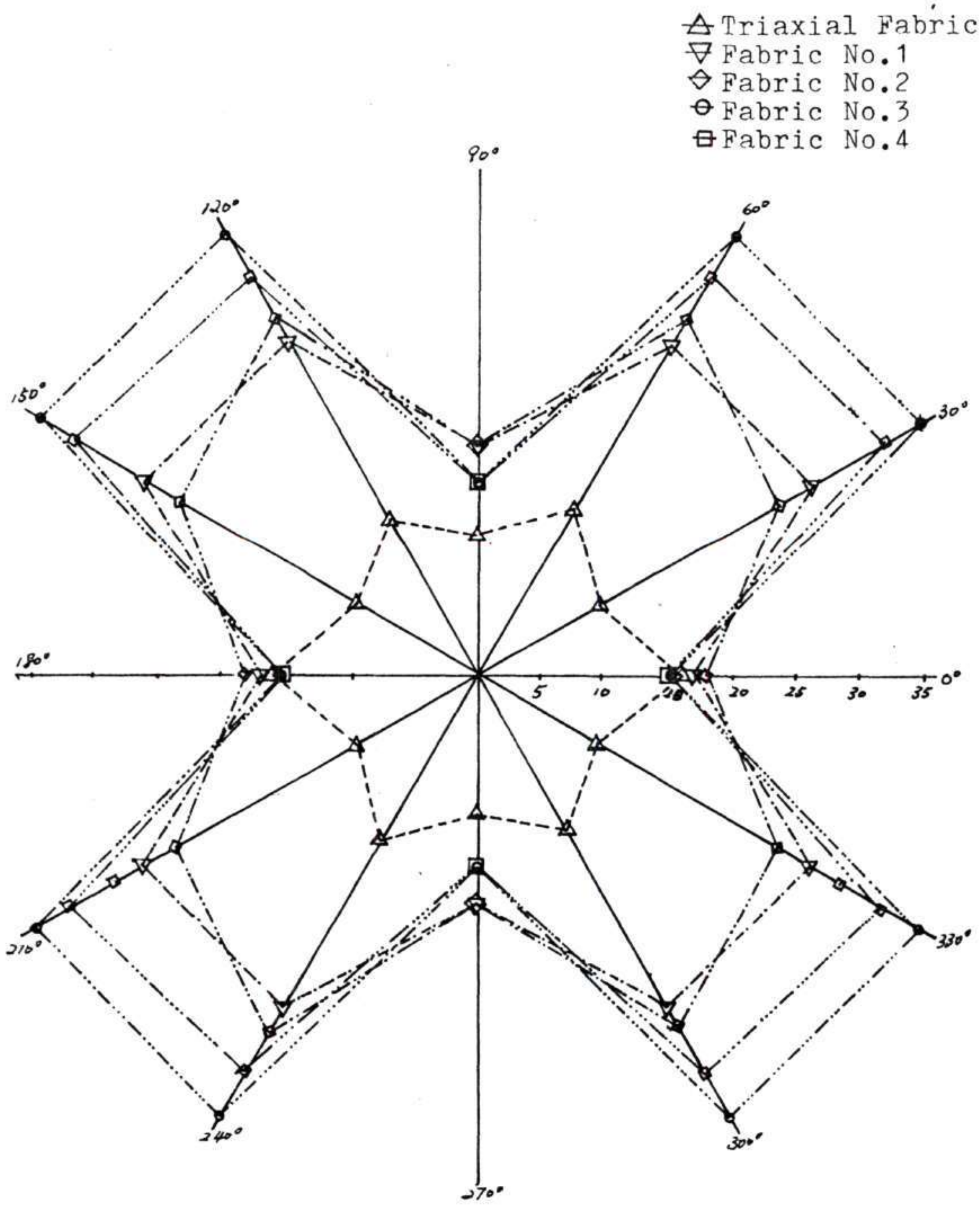
Rupture Load (lb./in.Width)

Figure 22. The Rupture Load of Various Fabrics in Different Directions(With test specimens of half an inch wide by five inches long between jaws)



Rupture Elongation (%)

Figure 23. The Rupture Elongation of Various Fabrics in Different Directions(With test specimens of three inches wide by three inches long between jaws)



Rupture Elongation (%)

Figure 24. The Rupture Elongation of Various Fabris in Different Directions(With test specimens of one inch by three inches long between jaws)

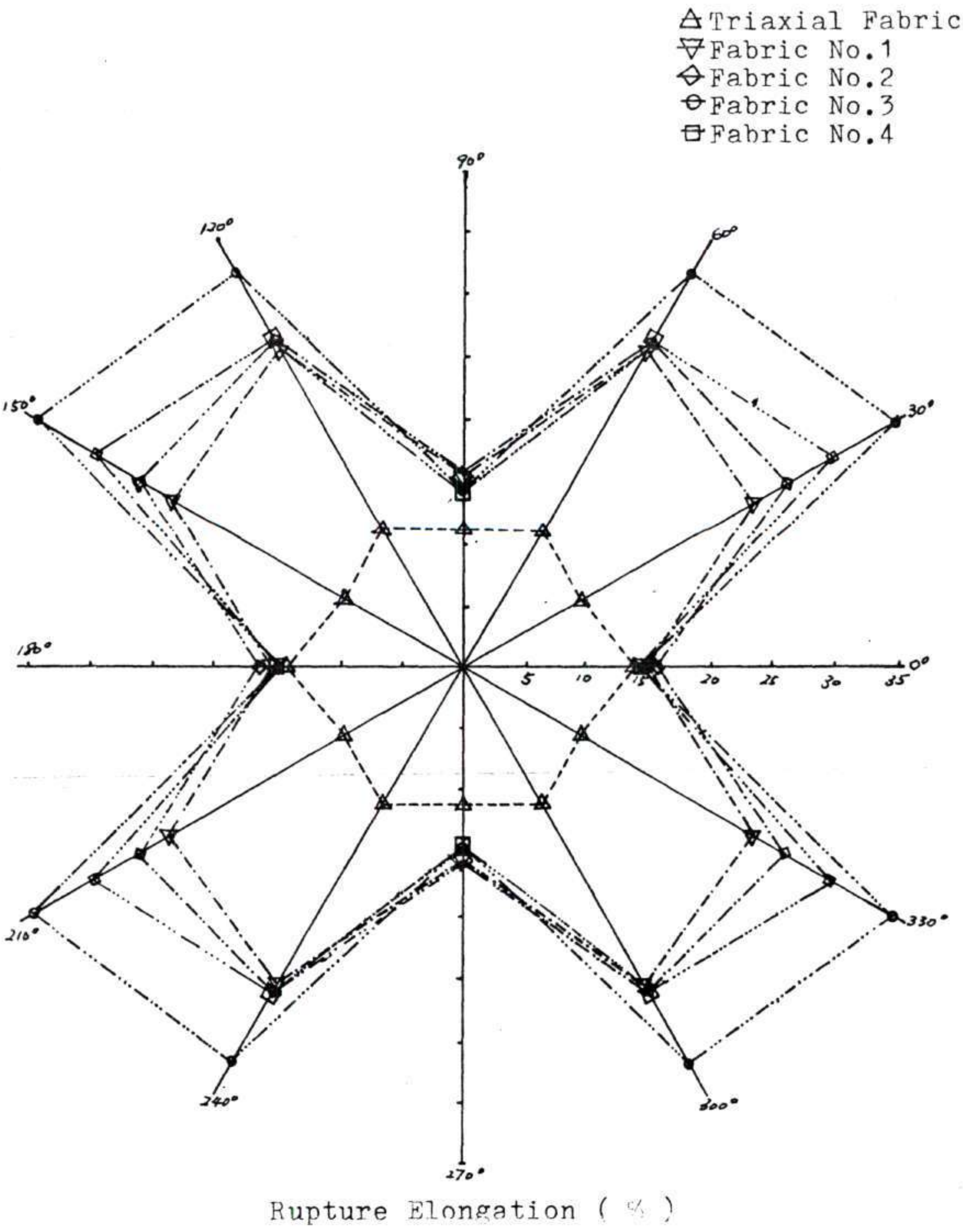
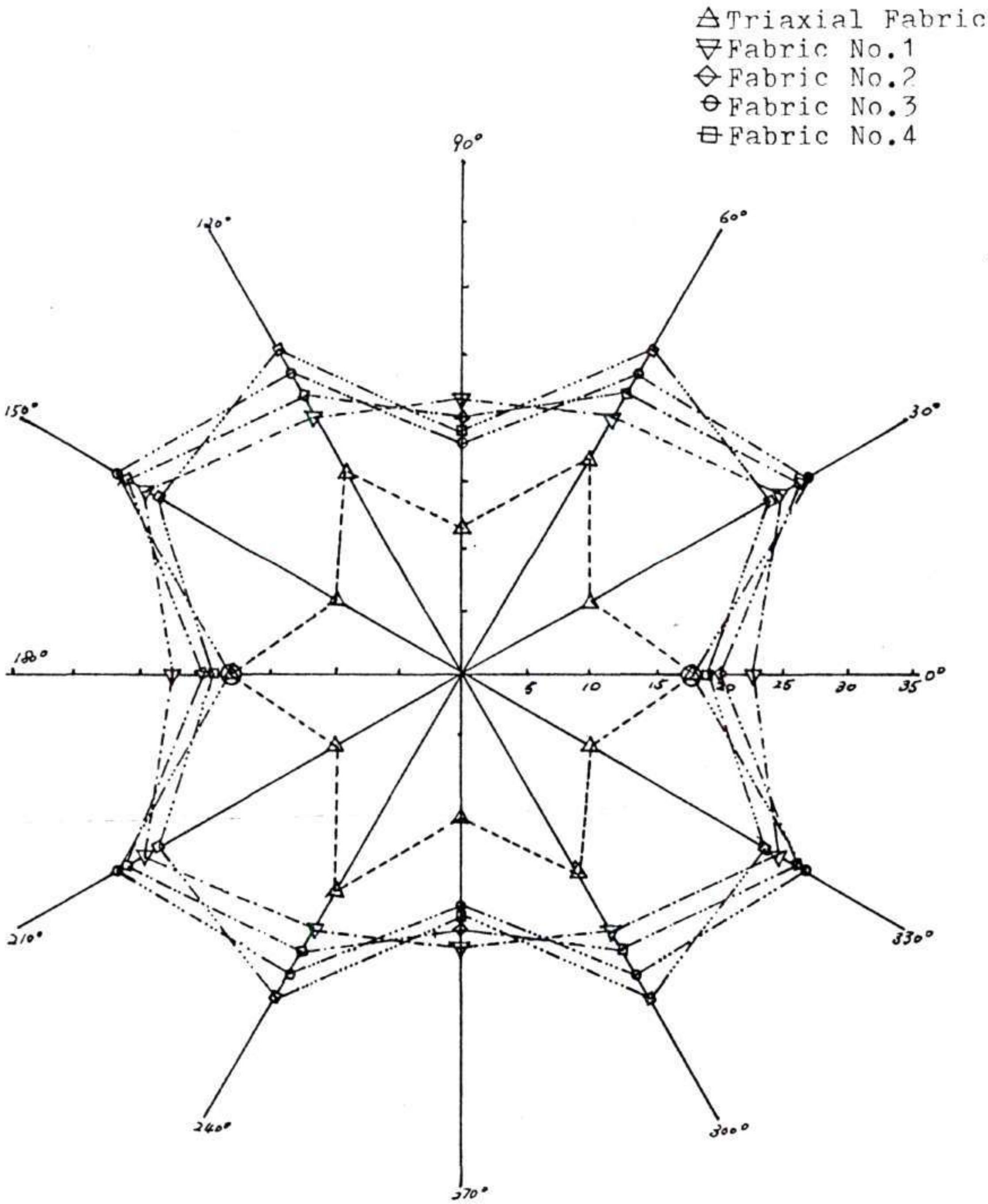
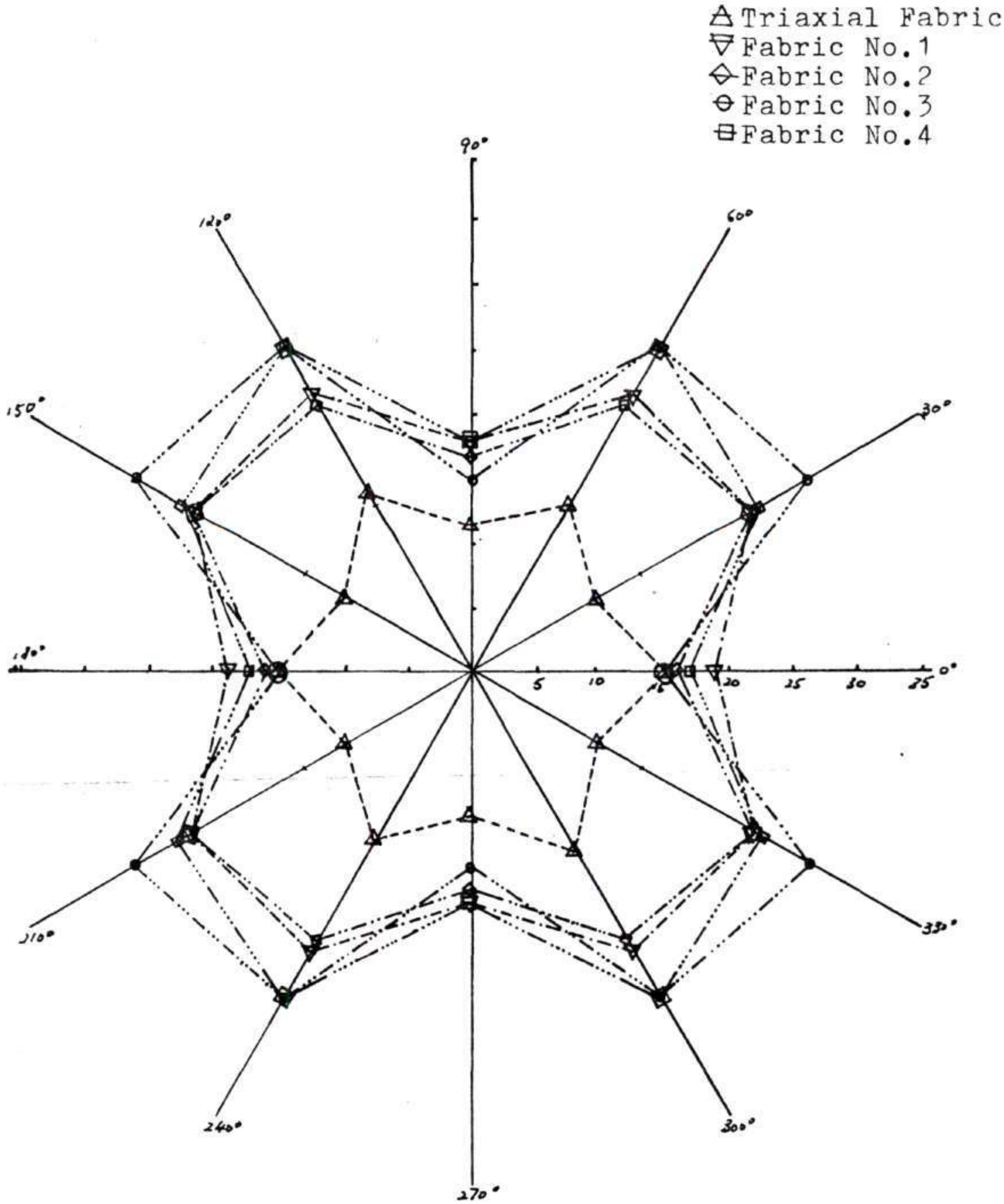


Figure 25. The Rupture Elongation of Various Fabrics in Different Directions(With test specimens of one inch by five inches long between jaws)



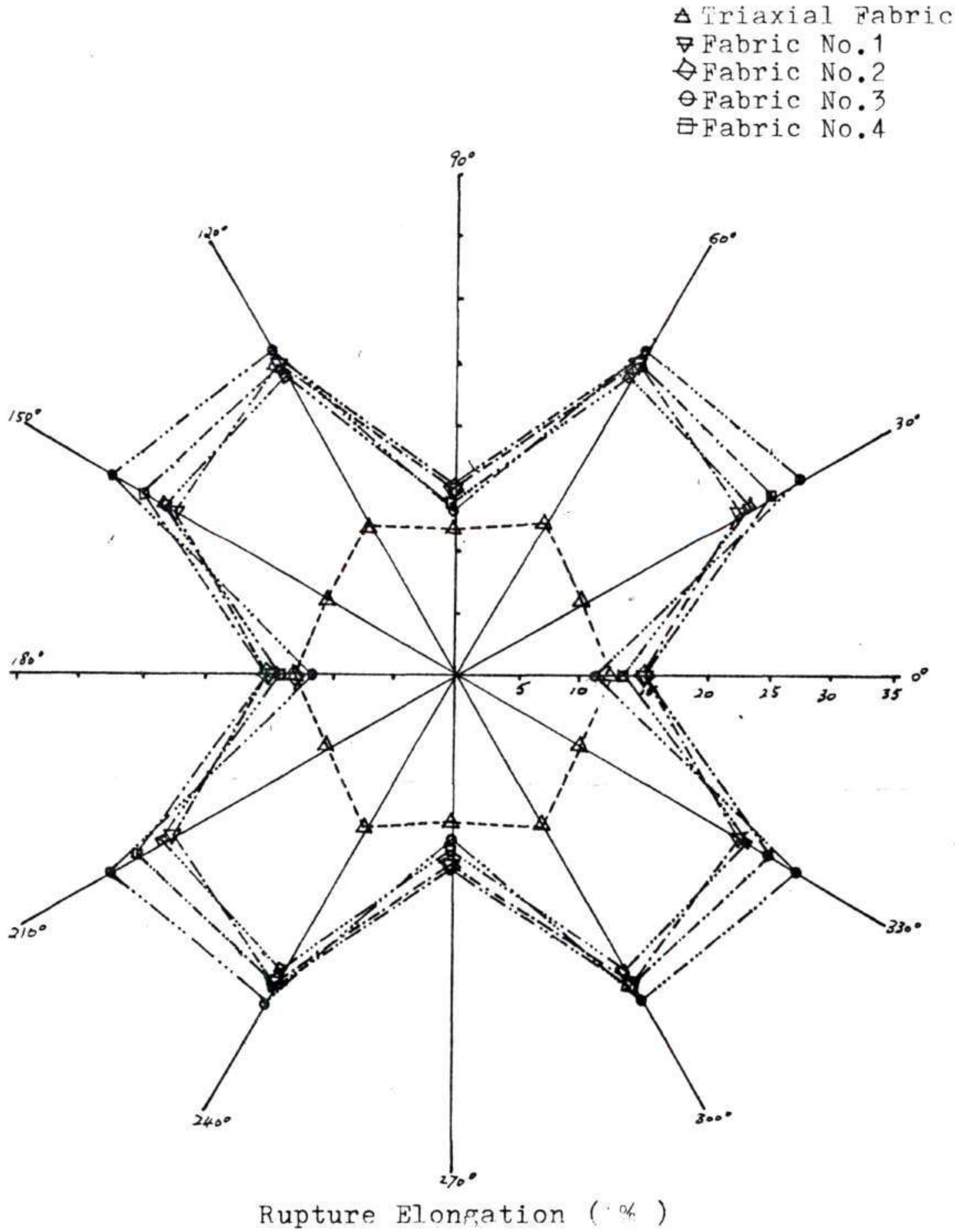
Rupture Elongation (%)

Figure 26. The Rupture Elongation of Various Fabrics in Different Direction(With test specimens of half an inch wide by one inch long between jaws)



Rupture Elongation (%)

Figure 27. The Rupture Elongation of Various Farics in Different Directions(With test specimens of half an inch by three inches long between jaws)



Rupture Elongation (%)

Figure 28. The Rupture Elogation of Various Fabrics in Different Directions(With test specimens of half an inch by five inches long between jaws)

give a rupture load approximately 30% higher than their counterpart in triaxial fabric because the triaxial fabric has one-third less yarns in both principal directions. When narrow specimens of biaxial and triaxial fabrics are tensile tested in other than principal directions, the rupture loads are much lower than in principal directions as a result of the lack of through-going-yarns.

Among all biaxial fabrics, only fabric No. 3 gives a comparatively higher rupture load when narrow specimens are tensile tested in other than principal directions. From the observations made during the experiment, the specimens of biaxial fabric No. 3 are extended by rotating the non-through-going yarns close to each other in the direction of the extension. Then, as the extension increases the non-through-going yarns in the middle portion of the specimen start jamming into each other and the jamming action is then gradually extended throughout the whole specimen. This jamming action locked most non-through-going yarns in the specimen at their crossover points and allowed them to act as through-going-yarns. Therefore, a higher rupture load can be obtained here. In other fabrics, including the triaxial fabric, the tested specimens collapsed under extension by pulling the structure apart before any jamming takes place.

These two different tensile behaviors observed above can be explained simply by considering the biaxial fabrics which consist in essence of trellises. When tensile loading is applied in other than principal directions, the biaxial fabrics tend to extend by rotating the memebers of trellises relative to each other and to change the config ration as shown in Figure 29. In fabric No. 3, the tight plain st

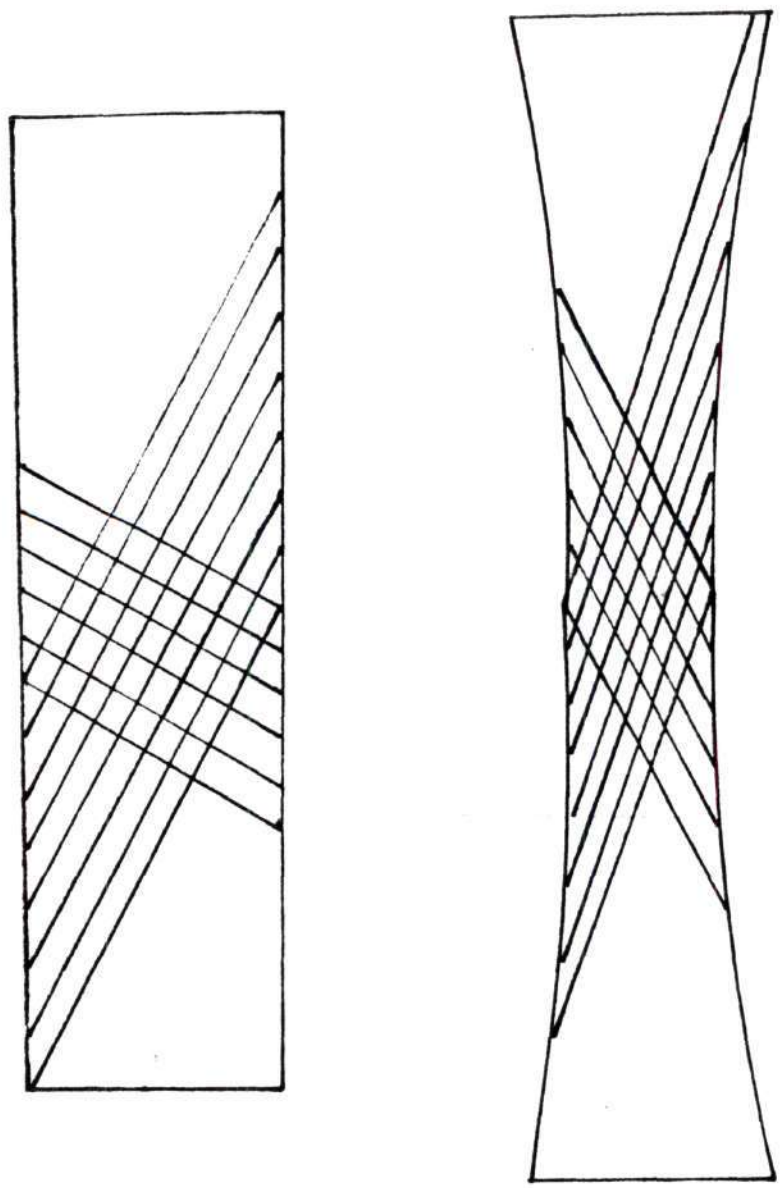
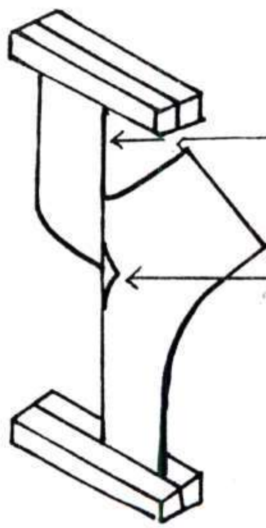


Figure 29. Tensile Behavior of Biaxial Fabric when Tested in other than Principal Directions



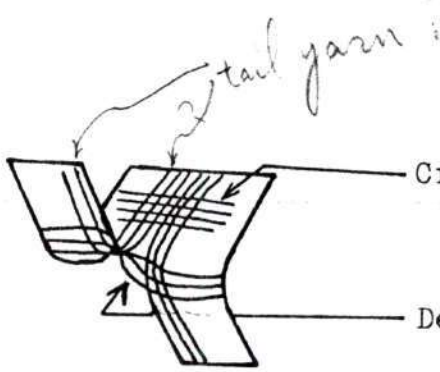


Figure 30. The Tongue Tear Test

provides a large number of yarn crossover points and leaves relatively small openings between yarns. Thus, it does not require a large degree of relative yarn rotation to change the configuration of the trellises before openings between the yarns are closed up and form a jamming condition in the fabric. On the other hand, the loose woven fabrics tend to provide fewer yarn crossover points and more opening areas between yarns; therefore, they need an extensively larger degree of yarn rotation and configuration changes in order to close up the opening and let the jamming condition occur in the fabric. In narrow width specimens, the non-through-going yarns are so short that they are always pulled out from the structure under extension before they can rotate close enough and lock each other at the crossover points to form a jamming condition and sustain a higher rupture load.

The triaxial fabric remains more isotropic than those comparable biaxial fabrics when three inches wide specimens are tensile tested. This is clearly demonstrated in the polar graph as shown in Figure 19. But, on the other hand, the triaxial fabric shows poorly in isotropic properties when narrow specimens are tensile tested. These narrow specimens yield extremely low rupture load in other than principal directions as a result of loose structural design and lack of through-going yarns. Thus, in future evaluations of tensile properties of triaxial fabric, wide specimens are recommended.

When narrow specimens of triaxial fabric are tensile tested in other than principal directions, both sets of non-through-going yarns in the direction of the extension tend to rotate relatively close to each other and to reduce the dimension of the width of the specimens in order to extend. But the third set of yarns in the width will resist this dimensional change and prevent the specimens from jamming before it collapses and yields a higher rupture load.

In this experiment, comparable modulu results from various fabrics are difficult to obtain. Apparently, the triaxial fabric has the lowest modulu in both principal and other than principal directions.

(7) Tearing Strength

In this experiment, comparable results from various fabrics are difficult to obtain when ASTM standard calculation methods (D2261-71.10) are used. With the ASTM standard calculation methods, the tearing strength of the fabric is measured in a fixed range between a quarter of an inch and three inches crosshead separations. In some of our loose woven fabric samples, no tearing but cross yarns shifting appears in this range. Thus, it does not represent the real tearing strength of the fabric. Due to this fact, a relative tearing range has to be used in order to obtain the real tearing strength of the fabric. With this modified method, the first peak appearing in the record chart is used as a mutual indicator where measurements should begin. This tends to give more accurate and comparable results among various fabrics. The detailed calculating procedures of this method are stated below:

1) Divide the record chart into equal portions, each representing a total of half an inch crosshead separation after test is set in motion;
2) Determine the highest peak value in each of the five successive portions following the portion where the first peak appears; and

3) Calculate the average of these five highest peak values.

The tearing strength of various fabrics are given in Table 12.

Table 12. Tearing Strength of Various Fabrics

	Triaxial Fabric	Biaxial Fabrics No.1	2	3	4
Filling Test (lb)	49	46	42	31	24
Warp Test (lb)	Warp at 60° 26 Warp at 120° 26	41	34	23	21
Max. Load Filling Test (lb)	105	94	55	47	30
Warp Test (lb)	Warp at 60° 37 Warp at 120° 42	89	42	37	37

The tearing strength of fabrics No. 1 and No. 2 is higher than that of fabrics No. 3 and No. 4 because heavier yarns are used. The tearing behavior of biaxial fabrics No. 1 and No. 3 differs significantly from fabrics No. 2 and No. 4 as a result of different fabric structures. In fabrics No. 1 and No. 3 the plain structures provide many yarn crossover points, thus the gripping action between the warp and filling threads tends to be high when tearing occurs. At the beginning of the tearing test, the cross yarns are pulled out into vertical plane and become del yarns which start to fail progressively under tension. As the tearing action goes on to a point where the fabric ahead of del is distorted and jammed, both the cross yarns and tail yarns are pulled parallel to the del yarns. Therefore, when a del yarn breaks, the snake back of the tail may cause another del yarn to break, but this time it may break one of the tail yarns which lay parallel to the del yarns and shifts the tearing action 90 to the tail.

In fabrics No. 2 and No. 4 the twill structures provide fewer yarn crossover points and give the yarns more freedom of movement. During the tearing test, the cross yarns can shift easily from the del toward the untorn fabric ahead and form a bundle which can support a much greater load than the tail can sustain; therefore, the tail fails before any rupture occurs in the cross yarns.

During the filling test, triaxial fabric yields the highest tearing strength among all other fabrics and has a very different tearing behavior from the biaxial structures. At the beginning of the tearing test, the cross yarns in the triaxial fabric specimens are locked between two different sets of tail yarns and are pulled toward the untorn fabric; then, as strain increases the fabric ahead of del is jammed and tearing thus takes place in the direction of the weakest set of yarns.

In all the tearing tests, the force required to cause tear is always greater than the force required to continue tear. This is because at the beginning of the tearing test, the first few cross yarns at the del are forced to shift close to each other and share the load. In order to cause tear in this condition, the tail yarns must break those cross yarns simultaneously. Thus, a greater force is required. On the other hand, to continue tear, the tail yarns break the cross yarns successively, one at a time; therefore, the force required is much lower.

(8) Ball Burst Strength

The ball burst strength in biaxial fabrics No. 1 and No. 3 are much higher than that of fabrics No. 2 and No. 4, respectively, because in fabrics No. 1 and No. 3 the plain structures provide many yarn crossover points; thus, the gripping action between warp and filling threads tends to be high. For this reason, the yarns rupture simultaneously as the ball bursts through during the test. In fabrics No. 2 and No. 4, the twill structures provide much less yarn crossover points and give the yarns more freedom of movement. Therefore, during the test, some of the yarns break first and others just slide aside and let the ball pass by.

In triaxial fabric, a comparably low strength is obtained because both sets of warps are interlaced with filling only, thus once the filling breaks, both sets of warps become two sheets of yarns which show little resistance as the ball forces through.

The ball burst strength of various fabrics are listed in Table 13.

Table 13. Ball Burst Strength of Various Fabrics

Fabric	Ball Burst Strength
Triaxial Fabric	210 lbs.
Biaxial Fabric No. 1	356 lbs.
No. 2	139 lbs.
No. 3	295 lbs.
No. 4	234 lbs.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

The triaxial fabric and a range of comparable biaxial fabrics were evaluated and compared for various structural and mechanical properties. The air permeability of triaxial fabric was found to be much greater than that of comparable biaxial fabrics with approximately the same percentage light transmission. The shear resistance of the triaxial fabric proved to be greater than that of comparable biaxial fabrics and could have been made even greater if the out-of-plane buckling of one of the sets of threads could be prevented. The tensile properties of triaxial fabric remained more isotropic than those of comparable biaxial fabrics only when wide specimens were tested. The triaxial fabric exhibited much greater isotropy in its bending behavior than that of comparable biaxial fabrics. The tearing response of the triaxial fabric was found to be quite different from that of comparable biaxial fabrics and yielded surprisingly high tearing strength when compared to biaxial fabrics. The ball burst strength of triaxial fabric proved to be lower than that of comparable biaxial fabrics.

In general, the triaxially woven fabric used in this program proved to be more isotropic than very closely woven biaxial fabrics with appriximately the same open area. It is this combination of stability and openness that has led to the historical uses in basketry, straw-work, and snowshoes; other similar uses would no doubt be found for the fabric if it were available in large quantities.

There are other aspects of the triaxially woven materials that are as yet completely unexplored. A great range of weave structures are possible that have no analogue in biaxial fabrics. Preliminary evaluation of basic plain woven triaxial fabrics has indicated that this plain structure might possess far superior mechanical properties and remain more closely isotropic than biaxial weaves. To evaluate this plain woven triaxial fabric in the future would be of great interest and importance to the development of textile materials.

Full exploration of the possibilities of various triaxial fabrics can only be carried out if adequate supplies of fabrics are available. There is no doubt that both the intrinsic scientific interest of the unusual triaxial structures and the importance of their possible areas of utilization warrant further effort in the field of development and fabric characterization.

APPENDIX

* Mean ($\bar{X}$): Arithmatic average of a set of observation.

$\bar{X} = \frac{\sum X}{n}$ X=Observation on Individual Data

n= Number of Observations

$\sum X$= Sum of Cbservations

* Standard Deviation (σ)

The square root of the average of the square of the devation of individuals from the mean. A measure of the variation of individual results.

$$\sigma = \sqrt{\frac{\Sigma X^2}{n} - \bar{X}^2}$$

* Coefficient of Variation (% CV.)

The standard deviation expressed as a percent of the mean.

$$\% \text{ CV.} = \frac{\sigma}{\bar{X}} \times 100$$

Table 14. Tensile Properties of Triaxial Fabric (With test specimens of three inches wide by three inches long between jaws)

	0°	30°	60°	90°	120°	150°
Rupture Load (lb./in.Width)	99 98 103 100 97	60 61.6 60 57 62	132 130 133 132 130	40 47 46 47 45	135 120 131 136 135	60 66 60.6 56.6 61
$\bar{X}$	99	60	131	45	131	61
σ	2.64	1.95	1.34	3.36	6.65	3.36
%C.V	2.6	3.2	1.0	7.4	5.0	5.5
Rupture Elongation (%)	14% 14.6% 14.6% 15.3% 14.5%	17.3% 18.3% 18% 16.6% 18%	17.6% 17.3% 16% 17.3% 16.6%	18% 18% 18% 18% 17.3%	18.3% 14% 17.3% 18% 17.3%	18% 17.3% 17.6% 17.3% 20%
$\bar{X}$	14.6%	17.5%	17%	18%	17%	18%
σ	0.53	0.68	0.65	0.35	1.7	1.1
%C.V	3.6	3.9	3.8	2.0	10.1	6.3
Modulus (lb./in.Width)	781 883 833 833 818	416 416 423 416 438	1041 1063 1111 1086 1162	250 263 256 294 264	1136 1063 1063 1136 1086	416 446 403 396 416
$\bar{X}$	820	421	1092	265	1096	415
	5-14%	5-14%	5-14%	5-14%	5-14%	5-15%

Table 15. Tensile Properties of Triaxial Fabric (With test specimens of one inch wide by three inches long between jaws)

	0°	30°	60°	90°	120°	150°
Rupture Load (lb./in.Width)	94	--	123	0.4	127	--
	97	--	123	0.5	128	--
	98	--	128	0.6	120	--
	99	--	126	0.55	112	--
	99	--	114	0.54	113	--
$\bar{X}$	97.4	--	122.8	0.51	120	--
σ	2.0	--	5.3	0.07	7.5	--
%C.V	2.1	--	4.4	13.8	6.3	--
Rupture Elongation (%)	16.6%	--	15.3%	12%	15.3%	--
	16%	--	15.3%	8.6%	15.6%	--
	15.6%	--	14.6%	13%	15.3%	--
	16%	--	15.3%	12%	12.3%	--
	16%	--	13.6%	10.6%	12.6%	--
$\bar{X}$	16%	--	15%	11.5%	14%	--
σ	0.4	--	0.7	1.9	1.6	--
%C.V	2.2	--	5.0	17.3	11.4	--
Modulus (lb./in.Width)	870	--	1153	15	1200	--
	857	--	1200	14	1250	--
	909	--	1250	15	1111	--
	882	--	1153	13	1111	--
	882	--	1200	17	1111	--
$\bar{X}$	880	--	1191	15	1156	--
	5-15%	----	5-13%	0-2%	5-13%	--

Table 16. Tensile Properties of Triaxial Fabric (with test specimens of one inch wide by five inches long between jaws)

	0°	30°	60°	90°	120°	150°
Rupture Load (lb./in.Width)	96	--	114	--	120	--
	96	--	120	--	126	--
	100	--	123	--	130	--
	96	--	120	--	124	--
	95	--	122	--	125	--
$\bar{X}$	96	--	120	--	125	--
σ	1.9	--	3.5	--	3.6	--
%C.V	2.0	--	2.9	--	2.9	--
Rupture Elongation (%)	13.5%	--	12.5%	--	13.2%	--
	13.5%	--	14%	--	14.2%	--
	14.5%	--	13.2%	--	13.7%	--
	14.5%	--	14.5%	--	13%	--
	14%	--	13.5%	--	14%	--
$\bar{X}$	14%	--	13.5%	--	13.5%	--
σ	0.5	--	0.8	--	0.5	--
%C.V	3.6	--	5.6	--	3.8	--
Modulus (lb./in.Width)	952	--	1176	--	1250	--
	952	--	1176	--	1250	--
	930	--	1290	--	1333	--
	909	--	1212	--	3333	--
	1000	--	1250	--	937	--
$\bar{X}$	948	--	1220	--	1220	--
	5-13%	--	5-13%	--	5-13%	--

Table 17. Tensile Properties of Triaxial Fabric
(With test specimens of half an inch wide by one inch long between jaws)

	0°	30°	60°	90°	120°	150°
Rupture Load (lb./in.Width)	95	---	128	0.05	125	--
	104	---	124	0.05	135	--
	94	---	120	0.05	120	--
	98	---	138	0.05	123	--
	98	---	134	0.05	123	--
$\bar{X}$	98	---	127	0.05	125	--
σ	4.5	---	7.3	0	5.7	--
%C.V	4.6	---	5.6	0	4.6	--
Rupture Elongation (%)	19%	---	18.5%	12%	18%	--
	19%	---	18%	11%	18.5%	--
	18%	---	18%	13%	20%	--
	17%	---	20%	9%	21%	--
	18%	---	16%	15%	21%	--
$\bar{X}$	18%	---	18%	12%	19.5%	--
σ	1.0	---	1.4	--	1.4	--
%C.V	5.2	---	7.1	--	7.9	--
Modulus (lb./in.Width)	689	---	1000	1.4	869	--
	714	---	1000	1.8	869	--
	699	---	909	1.7	800	--
	714	---	952	1.5	800	--
	705	---	1111	1.6	800	--
$\bar{X}$	704	---	994	1.6	838	--
	5-13%	---	5-13%	5-13%	5-13%	----

Table 18. Tensile Properties of Triaxial Fabric (With test specimens of half an inch wide by three inches long between jaws)

	0°	30°	60°	90°	120°	150°
Rupture Load (lb./in.Width)	100	--	118	--	122	--
	97	--	130	--	121	--
	98	--	122	--	130	--
	96	--	126	--	124	--
	96	--	124	--	127	--
$\bar{X}$	97	--	124	--	125	--
σ	1.6	--	4.4	--	3.7	--
%C.V	1.7	--	3.6	--	2.9	--
Rupture Elongation (%)	15.3%	--	15.6%	--	13%	--
	15.3%	--	15.6%	--	17%	--
	15.3%	--	14%	--	16.6%	--
	14.6%	--	15.3%	--	16.3%	--
	15.3%	--	15.6%	--	17%	--
$\bar{X}$	15.2%	--	15.2%	--	16%	--
σ	0.3	--	0.7	--	1.7	--
%C.V	2.1	--	4.6	--	10.6	--
Modulus (lb./in.Width)	882	--	1200	--	1250	--
	882	--	1200	--	1071	--
	909	--	1200	--	1250	--
	882	--	1250	--	1111	--
	882	--	1250	--	1200	--
$\bar{X}$	887	--	1220	--	1176	--
	5-13%	--	5-13%	--	5-13%	--

Table 19. Tensile Properties of Triaxial Fabric
(With test specimens of half an inch
wide by five inches long between jaws)

	0°	30°	60°	90°	120°	150°
Rupture Load (lb./in.Width)	88	--	124	--	128	--
	92	--	146	--	124	--
	92	--	115	--	118	--
	92	--	130	--	117	--
	91	--	129	--	120	--
$\bar{X}$	91	--	128	--	121	--
σ	1.7	--	13	--	4.5	--
%C.V	1.9	--	10.1	--	3.7	--
Rupture Elongation (%)	11%	--	13%	--	14%	--
	13.5%	--	15.5%	--	13%	--
	13.5%	--	13.7%	--	12.5%	--
	13.5%	--	14.7%	--	14.5%	--
	13%	--	15%	--	15.5%	--
$\bar{X}$	13%	--	14%	--	14%	--
σ	1.3	--	1.1	--	1.2	--
%C.V	9.7	--	7.7	--	8.6	--
Modulus (lb./in.Width)	952	--	1290	--	1333	--
	1000	--	1481	--	1333	--
	930	--	1142	--	1176	--
	909	--	1379	--	1176	--
	909	--	1320	--	1290	--
$\bar{X}$	940	--	1323	--	1261	--
	5-13%	--	5-13%	--	5-13%	--

Table 20. Tensile Properties of Biaxial Fabric No.1 (With test specimens of therr inches wide by three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	218	236	72.5	77
	210	225	66.6	71.5
	220	238	76.6	80.8
	200	241	75	68.3
	223	240	69	66.6
$\bar{x}$	214	236	72	72.8
σ	9.2	6.4	4.1	5.5
%CV.	4.3	2.7	5.7	7.6
Rupture Elongation (%)	19%	19%	26%	27%
	19%	17.3%	24.5%	26.5%
	20%	19%	26%	24.6%
	17.5%	19%	26.6%	26%
	20%	22%	23.3%	25.6%
$\bar{x}$	19%	19%	25%	26%
σ	1.0	2.0	1.4	0.9
%CV.	5.4	10	5.3	3.5
Modulus (lb./in.Width)	1428	1388	434	434
	1449	1639	425	430
	1449	1562	449	476
	1449	1587	425	439
	1408	1515	454	425
$\bar{x}$	1436	1537	437	440
	6-14%	6-14%	14-20%	14-20%

Table 21. Tensile Properties of Biaxial Fabric No.1 (With test specimens of one inch wide by three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	218	210	11.8	12
	220	215	10.8	12.4
	225	235	9.6	11.8
	225	210	13.2	10
	220	210	11.8	13
$\bar{x}$	221	216	11.4	11.8
σ	3.2	10.8	1.3	1.1
%CV.	1.4	5.0	11.6	9.5
Rupture Elongation (%)	18%	17%	33%	32%
	19%	16.6%	30%	30.6%
	17.6%	17.3%	29.6%	30.6%
	18.5%	17%	28%	29.3%
	18%	17%	30%	30%
$\bar{x}$	18%	17%	30%	30.5%
σ	0.5	0.2	1.8	1.0
%CV.	3.0	1.5	6.0	3.3
Modulus (lb./in.Width)	1744	1754	104	104
	1666	1829	88.8	104
	1704	1785	109	114
	1704	1744	104	104
	1704	1754	117	120
$\bar{x}$	1696	1773	104	109
	7-14%	7-14%	20-26%	20-25%

Table 22. Tensile Properties of Biaxial Fabric No.1 (with test specimens of one inch wide by five inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	225	240	12	9.4
	227	230	12.6	13.5
	220	240	12.2	10.4
	220	240	13.5	10
	212	235	12.6	11
$\bar{x}$	221	236	12.6	10.86
σ	5.8	4.4	0.5	1.5
%CV.	2.6	1.8	4.5	14.6
Rupture Elongation (%)	15.7%	15.5%	26.5%	27.5%
	16%	15%	25.2%	30.5%
	15.2%	15.5%	27.5%	29%
	15.5%	16%	28.5%	30%
	15%	15%	27.5%	29%
$\bar{x}$	15.5%	15.4%	27%	29%
σ	0.4	0.4	1.2	1.2
%CV.	2.6	2.7	4.6	3.9
Modulus (lb./in.Width)	2000	2105	110	123
	2083	2000	133	139
	1904	2105	128	110
	2083	2000	145	128
	1904	2051	123	128
$\bar{x}$	1995	2052	127	125
	6-11%	6-11%	20-28%	20-30%

Table 23. Tensile Properties of Biaxial Fabric No.1 (With test specimens of half an inch wide by one inch long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	228	242	1.6	2
	252	236	1.6	1.5
	232	242	1.8	1.6
	232	228	1.9	1.7
	232	248	1.6	1.9
$\bar{x}$	235	239	1.7	1.7
σ	9.5	7.5	0.15	0.2
%CV.	4.0	3.1	8.3	12
Rupture Elongation (%)	22.5%	22.5%	26%	23%
	21.5%	21.5%	27%	20%
	22.5%	22.5%	31%	27%
	20.5%	20.5%	29%	25%
	19.5%	19.5%	30%	20%
$\bar{x}$	21.5%	22.6%	28.6%	23%
σ	1.3	1.3	2.1	3.1
%CV.	6.1	6.1	7.3	13.4
Modulus (lb./in.Width)	1428	1428	10	11.8
	1538	1480	9.4	11.4
	1250	1333	8.8	10
	1666	1250	8.4	10.6
	1480	1200	8.4	12.3
$\bar{x}$	1472	1347	9	11.2
	0-15%	0-15%	12-18%	10-17%

Table 24. Tensile Properties of Biaxial Fabric No.1 (With test specimens of half inch wide by three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	246	236	1.9	2.2
	220	246	1.6	1.6
	196	252	2	2.2
	240	222	1.9	2
	228	240	1.7	1.6
$\bar{x}$	226	239	1.8	1.9
σ	19.5	11.3	0.17	0.3
%CV.	8.6	4.7	9.3	15.7
Rupture Elongation (%)	19.3%	19%	25.6%	25.5%
	17.6%	18.6%	22.3%	21%
	16%	18.8%	25.3%	24.5%
	19%	18.5%	26.3%	28%
	17%	18.7%	26%	26.6%
$\bar{x}$	18%	18.8%	25%	25%
σ	1.4	0.2	1.6	2.6
%CV.	7.8	1.0	6.4	10.5
Modulus (lb./in.Width)	1714	1714	11.6	12
	1690	1874	12	11.8
	1600	1846	17.4	15.4
	1690	1614	11.8	16
	1738	1750	11.4	15.4
$\bar{x}$	1686	1780	13	14
	6-11%	6-11%	15-18%	15-20%

Table 25. Tensile Properties of Biaxial Fabric No.1 (With test specimens of half an inch wide . by five inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	212	232	1.6	1.8
	234	216	1.7	1.9
	208	232	1.4	1.8
	208	230	1.6	1.9
	196	210	1.6	1.9
$\bar{x}$	212	224	1.6	1.9
σ	13.8	10.3	0.08	0.04
%CV.	6.5	4.5	5.3	2.5
Rupture Elongation (%)	15.5%	15.7%	26%	29%
	15.5%	15%	25.5%	30%
	14.5%	15.5%	26%	28.7%
	14.7%	15.5%	25.7%	29%
	15.5%	16%	26%	27.8%
$\bar{x}$	15%	15.5%	26%	29%
σ	0.5	0.4	0.2	0.8
%CV.	3.2	2.4	0.9	2.7
Modulus (lb./in.Width)	1828	2064	10.8	11.2
	1640	2000	12.3	11
	1828	2064	10.8	12.2
	1684	2000	10.8	11.8
	1776	2064	11.8	11.7
$\bar{x}$	1751	2038	11.3	11.6
	5-11%	5-11%	15-20%	15-20%

Table 26. Tensile Properties of Biaxial Fabric No.2 (With test specimens of three inches wide by three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	212	210	68.3	63.3
	214	207	59	62.3
	215	222	50	70
	215	207	55	71
	215	215	68.3	65
$\bar{x}$	214	212	60	64
σ	1.0	6.3	8.1	3.9
%CV.	0.6	3.0	13.5	5.9
Rupture Elongation (%)	17%	19%	38%	41.6%
	17%	19%	37%	33.6%
	17%	17%	40%	35.3%
	16.6%	18%	32%	34%
	16.6%	19%	36%	38%
$\bar{x}$	17%	18.4%	36.7%	36.5%
σ	0.2	0.9	3.0	3.3
%CV.	1.3	4.9	8.1	9.1
Modulus (lb./in.Width)	1562	1492	232	209
	1612	1470	256	288
	1612	1621	161	227
	1666	1515	277	232
	1612	1492	250	200
$\bar{x}$	1612	1518	235	231
	9-16%	11-17%	12-17%	12-17%

Table 27. Tensile Properties of Biaxial Fabric No.2 (With test specimens of one inch wide by three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	245	237	2.25	1.2
	245	217	2.15	1.6
	255	240	2.5	1.77
	245	230	2.6	1.65
	260	235	3	1.45
$\bar{x}$	250	232	2.5	1.53
σ	7.0	9.0	0.33	0.22
%CV.	2.8	3.9	13.3	14.2
Rupture Elongation (%)	18.6%	17.6%	29%	30.6%
	18%	18%	26.6%	31.3%
	18.3%	18.6%	27.3%	35.3%
	17%	18%	26.6%	29%
	18.6%	18%	27%	36%
$\bar{x}$	18%	18%	27.3%	32.4%
σ	0.7	0.4	1.0	3.1
%CV.	3.7	2.0	3.6	9.4
Modulus (lb./in.Width)	1666	1428	0.83	0.75
	1764	1714	0.93	0.81
	1875	1769	1.07	0.73
	1818	1764	1.07	0.76
	1818	1818	1.07	0.72
$\bar{x}$	1788	1697	1	0.75
	6-13%	8-14%	0-9%	0-13%

Table 28. Tensile Properties of Biaxial Fabric No.2 (With test specimens of one inch wide by five inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	212 215 207 222 222	215 217 230 237 245	2.3 2.1 1.9 2.2 1.5	1.4 1.35 1.5 1.6 1.4
$\bar{x}$	216	229	2	1.45
σ	6.4	12.8	0.32	0.1
%CV.	3.0	5.6	15.8	6.9
Rupture Elongation (%)	16.5% 14% 15.5% 14% 15%	15% 14.5% 16% 16% 16%	29% 30% 29% 29% 29%	31% 30% 30% 34% 31%
$\bar{x}$	15%	15.5%	29%	31%
σ	1.1	0.7	0.4	1.6
%CV.	7.1	4.6	1.5	5.3
Modulus (lb./in.Width)	1702 2173 1777 2173 2127	2000 2105 2105 2051 2222	2 2.1 2 2 1.75	2.5 1.8 1.7 1.6 2.2
$\bar{x}$	2000	2107	2	1.95
	6-12%	7-13%	7-15%	9-17%

Table 29. Tensile Properties of Biaxial Fabric No.2 (With test specimens of half an inch by one inch long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	224	216	0.38	0.34
	214	224	0.32	0.38
	256	236	0.3	0.34
	240	240	0.34	0.38
	242	---	0.3	0.34
$\bar{x}$	235	230	0.32	0.35
σ	16.4	11	0.033	0.022
%CV.	7.0	4.8	10.2	6.1
Rupture Elongation (%)	20%	20%	28%	23%
	22.7%	21%	24%	25%
	19%	18.5%	34%	26.5%
	22%	22%	30%	24.5%
	19%	---	29%	22.5%
$\bar{x}$	20.5%	20.3%	29%	25%
σ	1.7	1.5	3.6	1.6
%CV.	8.4	7.3	12.4	6.6
Modulus (lb./in.Width)	1379	1212	0.62	0.86
	1538	1333	0.66	1.2
	1538	1600	0.3	0.76
	1739	1428	0.46	1.28
	1538	---	0.42	0.86
$\bar{x}$	1542	1393	0.5	1
	5-13%	5-13%	0-11%	0-9%

Table 30. Tensile Properties of Biaxial Fabric No.2 (With test specimens of half an inch wide by three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	228	228	0.21	0.2
	246	218	0.23	0.2
	232	200	0.16	0.14
	222	196	0.22	0.15
	228	208	0.13	---
$\bar{x}$	231	210	0.2	0.17
σ	9.0	13.1	0.04	0.32
%CV.	3.8	6.2	22.6	18.5
Rupture Elongation (%)	17.3%	14.6%	24%	24%
	18.1%	17.2%	24.3%	25.6%
	17.6%	16.6%	25%	25%
	16%	16%	24.5%	26%
	17.3%	16.6%	22%	---
$\bar{x}$	17.2%	16.2%	24%	25%
σ		1.0	1.2	0.9
%CV.	4.5	6.1	4.8	3.5
Modulus (lb./in.Width)	1846	1934	0.25	0.35
	1818	1874	0.28	0.38
	1834	1714	0.32	0.32
	1874	1764	0.36	0.36
	1874	1764	0.34	---
$\bar{x}$	1849	1810	0.31	0.35
	6-12%	7-14%	0-11%	0-11%

Table 31. Tensile Properties of Biaxial Fabric No.2
(With test specimens of half an inch wide by five inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	218	212	0.36	0.3
	216	212	0.4	0.32
	236	216	0.46	0.4
	220	210	0.4	0.28
	220	204	---	0.38
$\bar{x}$	222	211	0.45	0.32
σ	8.0	4.4	0.04	0.05
%CV.	3.6	2.0	10	16
Rupture Elongation (%)	15.5%	15%	26%	27%
	14.7%	15.5%	32%	26%
	15.7%	14.5%	29%	28%
	14.4%	15%	28.5%	28%
	15%	14.5%	---	30%
$\bar{x}$	15%	15%	29%	28%
σ	0.5	0.4	2.5	1.5
%CV.	3.5	2.8	8.5	5.3
Modulus (lb./in.Width)	2000	2103	0.3	0.26
	1903	2104	0.28	0.36
	2103	1860	0.32	0.36
	2103	2159	0.36	0.32
	2103	1775	---	0.28
$\bar{x}$	2042	2000	0.31	0.31
	5-11%	5-11%	0-12%	0-12%

Table 32. Tensile Properties of Biaxial Fabric No.3
(With test specimens of three inches wide
by three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	135	168	59	54.6
	146	169	72.6	54.6
	145	167	66.6	59
	141	167	68.3	56.6
	146	168	76.6	65
$\bar{x}$	143	168	68.8	58
σ	4.7	0.83	6.6	4.3
%CV.	3.3	0.5	9.6	7.4
Rupture Elongation (%)	16.6%	18%	26%	22%
	18%	18%	26%	23%
	16.6%	17.3%	24%	25%
	17.3%	18%	29%	24%
	18%	18%	27%	25%
$\bar{x}$	17.3%	18%	26.4%	23.8%
σ	0.7	0.3	1.8	1.3
%CV.	4.0	1.8	6.9	5.5
Modulus (lb./in.Width)	1136	1162	245	263
	1162	1190	294	287
	1190	1280	289	256
	1190	1219	238	256
	1190	1219	294	277
$\bar{x}$	1173	1214	272	267
	6-15%	6-15%	7-17%	8-16%

Table 33. Tensile Properties of Biaxial Fabric No.3 (With test specimens of one inch wide by three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	146	180	61.5	55
	142	180	71.5	45.5
	143	187	66.5	52.5
	142	177	67	52
	145	150	60	46
$\bar{x}$	144	175	65.3	58
σ	1.8	14.3	4.6	4.2
%CV.	1.2	8.2	7.0	8.4
Rupture Elongation (%)	15.5%	16.5%	39%	39%
	15%	16%	40%	40%
	15%	17.5%	43%	40%
	15%	15%	40%	38%
	15%	15.5%	40%	40%
$\bar{x}$	15%	16%	40%	39.4%
σ	0.2	1.0	1.5	0.9
%CV.	1.5	6.0	3.8	2.3
Modulus (lb./in.Width)	1315	1562	312	263
	1339	1630	329	214
	1363	1482	309	256
	1315	1774	300	270
	1315	1339	277	277
$\bar{x}$	1329	1551	305	256
	7-13%	7-13%	23-30%	24-29%

Table 34. Tensile Properties of Biaxial Fabric No.3 (With test specimens of one inch wide by five inches long between)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	130 135 133 155 157	167 172 162 172 176	58 72 64 61 61	52.5 52.5 52 50 53
$\bar{x}$	142	170	63	52
σ	13	5.4	5.3	1.1
%CV.	9.1	3.1	8.4	2.2
Rupture Elongation (%)	13.5% 13.5% 13.5% 14.5% 15%	13.5% 14% 14% 14% 14%	39% 43% 43% 38% 41%	38% 38% 37% 36% 38%
$\bar{x}$	16%	14%	41%	37.4%
σ	0.8	0.2	2.1	0.9
%CV.	5.9	1.6	5.2	2.4
Modulus (lb./in.Width)	1449 1470 1470 1612 1612	1785 1754 1666 1754 1754	294 338 344 370 344	290 294 298 322 294
$\bar{x}$	1522	1742	338	299
	7-11%	7-11%	26-36%	22-30%

Table 35. Tensile Properties of Biaxial Fabric No.3
(With test specimens of half an inch wide by one inch long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	168	176	11.8	12.8
	140	184	13	12.6
	140	184	16.2	13.2
	158	180	12.2	11.8
	164	160	11.6	9.8
$\bar{x}$	154	177	13	12
σ	13.2	10	2.3	1.2
%CV.	8.6	5.6	15.5	11.6
Rupture Elongation (%)	18%	18.5%	30%	24%
	20%	19.5%	32%	27%
	16%	19%	34%	27%
	21%	17.5%	32%	28%
	18%	17%	31%	27%
$\bar{x}$	18.6%	18.3%	32%	27%
σ	1.9	1.0	1.5	1.5
%CV.	10.5	5.7	4.7	5.7
Modulus (lb./in.Width)	1081	1290	160	125
	1025	1290	154	174
	1250	1290	166	160
	1025	1333	133	142
	1025	1290	142	117
$\bar{x}$	1081	1298	151	143
	6-14%	8-17%	23-30%	18-28%

Table 36. Tensile Properties of Biaxial Fabric No.3
(with test specimens of half an inch wide
by three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	138	168	14.4	9.6
	138	173	11.6	10.8
	140	146	9.2	9.2
	139	160	13.8	14.6
	138	---	12.3	9.2
				8.6
$\bar{x}$	139	160	12	11
σ	0.9	11.7	2.0,	2.2
%CV.	0.6	7.2	16.7	21.4
Rupture Elongation (%)	15%	15.3%	30%	30.6%
	13.5%	15%	30.6%	30%
	15%	14.3%	30%	25%
	15%	13%	32%	28.6%
	14.5%	---	29.3%	28.6%
				27.3%
$\bar{x}$	14.6%	14.4%	30%	29%
σ	0.7	1.0	1.0	2.0
%CV.	4.5	7.1	3.3	7.1
Modulus (lb./in.Width)	1304	1620	100	100
	1333	1714	130	104
	1304	1500	115	111
	1395	1578	130	130
	1363	----	125	100
				85
$\bar{x}$	1340	1603	120	105
	7-12%	9-15%	23-30%	18-28%

Table 37. Tensile Properties of Biaxial Fabric No.3 (With test specimens of half an inch wide, by five inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	148	154	14.2	10.4
	130	172	14.4	10.6
	150	166	18	11.2
	144	164	17.2	12.2
	146	162	12.2	8.8
$\bar{x}$	144	164	15	11
σ	7.9	6.2	1.8	1.3
%CV.	5.5	4.0	14.5	11.2
Rupture Elongation (%)	13.5%	11%	29%	31%
	12%	12%	34%	28%
	14%	12.5%	35%	34%
	13.5%	12%	30%	30%
	13.5%	12.5%	32%	30%
$\bar{x}$	13.5%	12%	32%	30%
σ	0.8	0.5	2.5	2.2
%CV.	5.7	5.1	8.0	7.2
Modulus (lb./in.Width)	1481	1428	95	64
	1600	1538	86	57
	1538	1428	100	62.5
	1428	1428	100	74
	1538	1333	82	50
$\bar{x}$	1517	1431	92	61
	5-11%	5-10%	23-30%	18-28%

Table 38. Tensile Properties of Biaxial Fabric No.4 (With test specimens of three inches wide, three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	133	175	68	76
	160	166	76	73
	130	176	74	67
	148	181	93	80
	151	173	63	78
$\bar{x}$	144	174	75	75
σ	12.6	5.4	11.3	5.0
%CV.	8.7	3.1	15.2	6.7
Rupture Elongation (%)	14%	18.6%	28%	31.3%
	18.6%	16.6%	29%	30%
	13.3%	19.3%	28%	28.6%
	16.6%	18.6%	27%	32.6%
	16%	17%	28%	34%
$\bar{x}$	15.7%	18%	28%	31%
σ	2.1	1.2	0.7	2.1
%CV.	13.5	6.4	2.5	6.8
Modulus (lb./in.Width)	1126	1302	270	230
	1190	1237	270	223
	1162	1250	285	250
	1250	1282	295	217
	1190	1314	234	220
$\bar{x}$	1183	1277	271	228
	5-10%	8-15%	8-20%	6-17%

Table 39. Tensile Properties of Biaxial Fabric No.4 (With test specimens of one inch wide by three inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	130	182	28	25
	143	190	25	17
	141	190	25	22
	148	180	27	21
	148	180	27	--
$\bar{x}$	142	184	26	21.5
σ	7.3	5.1	1.3	3.3
%CV.	5.1	2.8	5.0	15.5
Rupture Elongation (%)	13.6%	17.3%	38%	37%
	14.6%	18.3%	36%	33%
	15.6%	18.6%	36%	34%
	16%	18%	35%	38%
	16%	17.3%	39%	---
$\bar{x}$	15%	18%	37%	35%
σ	1.0	0.6	1.6	2.4
%CV.	6.9	3.3	4.5	6.7
Modulus (lb./in.Width)	1270	1363	156	125
	1200	1428	156	150
	1250	1500	163	157
	1153	1428	159	133
	1304	1463	153	---
$\bar{x}$	1236	1436	157	141
	5-10%	9-15%	23-36%	25-34%

Table 40. Tensile Properties of Biaxial Fabric No.4
(With test specimens of one inch with by five inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	133	170	17.5	14
	134	175	19	14.5
	146	177	21	14.5
	145	180	18	14
	148	177	--	14.5
$\bar{x}$	141	176	19	14.3
σ	7.1	3.7	1.5	0.27
%CV.	5.0	2.0	8.2	1.9
Rupture Elongation (%)	13%	15%	34.5%	30%
	13%	14%	33%	32%
	15%	14.5%	31.7%	31.7%
	14%	15%	34.7%	30%
	15%	15%	---	30.7%
$\bar{x}$	14%	14.7%	33.5%	31%
σ	1.0	0.4	1.4	0.9
%CV.	7.1	3.0	4.2	3.1
Modulus (lb./in.Width)	1351	1666	193	200
	1428	1777	200	177
	1379	1739	217	163
	1428	1777	192	140
	1000	1702	---	145
$\bar{x}$	1317	1732	200	165
	5-9%	8-12%	25-30%	24-27%

Table 41. Tensile Properties of Biaxial Fabric No.4 (With test specimens of half an inch wide by one inch long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	152	170	2	2.2
	160	174	2	1.8
	150	188	2	1.8
	154	180	2.6	2.2
	152	184	--	2.5
$\bar{x}$	153	179	2.1	2.1
σ	3.8	7.3	0.3	0.3
%CV.	2.5	4.0	13.9	14.3
Rupture Elongation (%)	21%	18.5	27%	29%
	17.5%	18.%	26%	27.5%
	20%	18.5%	26%	29.5%
	19.5%	[illegible]	30%	28%
	20%	20%	--	29%
$\bar{x}$	19.6%	19%	27%	28.6%
σ	1.3	0.8	1.9	0.8
%CV.	6.6	4.0	6.9	2.9
Modulus (lb./in.Width)	1081	1142	14	14.2
	1212	[illegible]	15	11.6
	1081	1281	15	10.8
	1212	1250	20	13.6
	1142	1142	--	15.2
$\bar{x}$	1145	1187	16	13
	0-12%	0-13%	17-25%	15-24%

Table 41. Tensile Properties of Biaxial Fabric No.4
(With test specimens of half an inch wide
by one inch long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	152	170	2	2.2
	160	174	2	1.8
	150	188	2	1.8
	154	180	2.6	2.2
	152	184	--	2.5
$\bar{x}$	153	179	2.1	2.1
σ	3.8	7.3	0.3	0.3
%CV.	2.5	4.0	13.9	14.3
Rupture Elongation (%)	21%	18.5	27%	29%
	17.5%	18.[illegible]%	26%	27.5%
	20%	18.5%	26%	29.5%
	19.5%	19%	30%	28%
	20%	20%	--	29%
$\bar{x}$	19.6%	[illegible]	27%	28.6%
σ	1.3	0.8	1.9	0.8
%CV.	6.6	4.0	6.9	2.9
Modulus (lb./in.Width)	1081	1142	14	14.2
	1212	[illegible]	15	11.6
	1081	1261	15	10.8
	1212	1250	20	13.6
	1142	1142	--	15.2
$\bar{x}$	1145	1187	16	13
	0-12%	0-13%	17-25%	[illegible]-24%

Table 4[illegible]. Tensile Properties of Biaxial Fabric No.4
(With test specimens of half an inch wide
by three inches long between jaws)

		Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)		142	168	2.9	1.6
		148	172	2.5	1.0
		152	172	1.8	1.8
		146	170	2.5	1.8
		150	160	2.3	2
	$\bar{x}$	147	168	2.4	1.6
	σ	3.8	5.0	0.4	0.4
	%CV.	2.5	4.0	14	14
Rupture Elongation (%)		18%	16.6%	23%	27.6%
		16.6%	16.6%	28%	27.3%
		16.6%	18%	23.6%	29.3%
		18%	16.6%	26%	27.3%
		16.6%	15.6%	26.6%	30%
	$\bar{x}$	17%	16.6%	25.4%	28.3%
	σ	0.8	0.9	2.1	1.3
	%CV.	4.5	5.1	8.2	4.5
Modulus (lb./in.Width)		1000	1332	33	17.6
		1268	1332	28	22.2
		1276	1296	24	17.6
		1200	1410	30	20
		1230	1296	25	23
	$\bar{x}$	1194	1333	28	20
		5-11%	8-15%	20-25%	21-27%

Table 43. Tensile Properties of Biaxial Fabric NO.4
(With test specimens of half an inch wide by five inches long between jaws)

	Warp 90	Filling 0	30	60
Rupture Load (lb./in.Width)	128	168	2.2	1.6
	128	156	1.9	1.3
	140	146	1.8	1.7
	136	168	2	1.8
	126	150	2	1.6
$\bar{x}$	131	157	2.0	1.6
σ	6.0	10	0.14	0.18
%CV.	4.6	6.4	7.4	11.7
Rupture Elongation (%)	14%	14.25%	26.75%	26%
	15%	14%	25.5%	25.5%
	14.5%	12%	29%	27.75%
	15%	13.5%	28.5%	27.75%
	15.2%	13.5%	30%	28%
$\bar{x}$	14.75%	13.45%	28%	27%
σ	0.5	0.9	1.9	1.2
%CV.	3.4	6.5	6.5	4.3
Modulus (lb./in.Width)	1230	1333	30	20
	1142	1332	25	17
	1162	1454	18	21
	1084	1600	17	22
	1102	1390	22	22
$\bar{x}$	1144	1421	22	20
	4-8%	6-11%	22-26%	22-25%

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